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Design of a Combined Sewer Fluidic Regulator

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149

Design of a Combined Sewer Fluidic Regulator

The Development of Basic Configurations
and Design Criteria for Applications
of Fluidics in Sewer Regulators

FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
DEPARTMENT OF THE INTERIOR

by

Bowles Engineering Corporation
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FWPCA Review Notice

This report has been reviewed by the Federal Water Pollution Control Administration and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Federal Water Pollution Control Administration.

ABSTRACT

The objective of this program was to demonstrate feasibility, and to develop a workable configuration for a combined sewer Fluidic regulator, whose purpose is to minimize combined sewer discharge while protecting interceptor sewers from overloading during storm flows. A second objective was to develop design procedures and criteria for the general application of this concept to municipal sewer diversion requirements, including preliminary investigations of construction methods, costs, and maintenance requirements. A third objective was to establish a plan and location for an operational demonstration of the concept with a cooperating municipality.

All objectives were successfully met. A generic Fluidic Regulator configuration was evolved which diverts 0 to 75% of the combined sewer flow away from the interceptor as a function of water level sensed in the interceptor sewer, or combined sewer, in either an analog or digital operational mode. Application design criteria were evolved for a range of small to medium sized municipal sewers, in terms of a few basic parameters. Projected installation costs are only slightly more than for conventional diversion structures; while the anticipated construction and maintenance requirements are simple and minimal.

The City of Philadelphia was established as the demonstration site, and a demonstration unit should become operational in late 1970. Recommendations were made for experimental activity to improve regulation linearity; expand application size limit, and to better definitize construction methods and costs.

This report is submitted in fulfillment of Contract 14-12-486, between the Federal Water Pollution Control Administration and the Bowles Engineering Corporation.

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SECTION 1

CONCLUSIONS AND RECOMMENDATIONS

Conclusions*

1. The concept of a Combined Sewer Fluidic Regulator was found feasible and practical, based on a series of scale model tests in which the scale factor varied from about 1:6 to 1:20 of a "typical" municipal diversion sewer. Of the three basic fluidic arrangements tested, (geometric bias, fixed orifice bias, and variable orifice bias) only the variable orifice bias provided complete, predictable analog flow diversion. The fixed orifice bias provided good partial analog, or fully digital flow diversion, which may be quite satisfactory for many system applications. The geometric bias arrangement was abandoned early in the test program. While mechanically simplest, it proved to be overly sensitive to dimensional tolerances, and provided a significantly poorer range of flow diversion performance.

2. A basic Fluidic element geometry was developed which reliably diverts from 0 to greater than 75% of the combined flow from the interceptor to the receiving waters outlet as either a digital or proportional function of water level variation in either interceptor or combined sewer. This characteristic has been demonstrated over a considerable range of inlet heads. At low inlet heads (corresponding basically to dry weather flow), all the flow enters the interceptor. The unit's performance remains relatively unaffected by variations in inlet height-width ratio that would be encountered in adapting to the normal range of municipal installations.

3. A design rationale has been evolved for establishing the principal Fluidic Element geometric parameters to correspond to the normal range of municipal combined sewer regulator requirements.

4. A preliminary analysis has shown that the installation of a Combined Sewer Fluidic Regulator is similar in nature and overal complexity to a conventional leaping weir, or side flow diversion structure. It is estimated that the use of a Fluidic regulator would not increase the cost of a large diversion structure, and would add only about 20% to the cost of a small diversion structure. It is estimated that the modification of an existing structure for a Fluidic Regulator would cost 20 to 50% of the original installation cost, depending on size and degree of rework required.

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*Terminology related to Fluidic technology is described in the Glossary.

5. A simulated fouling test has shown a very low susceptibility to fouling by solid or soft sheet-like debris in the water flow. It is concluded that fluidic sewer regulators will require significantly less maintenance and/or surveillance to assure proper operation in municipal service.

Recommendations

1. It is recommended that a full scale pilot model of a Combined Sewer Fluidic Regulator be constructed, tested and evaluated in a typical municipal diversion point, or equivalent, based on the design criteria developed in the subject program. The unit should be operated on typical combined sewer flows, incorporating both normal dry weather and storm flows. The installation should be adequately instrumented to provide real time and recorded readings of all pertinent levels, flows, and control/sensor pressures. The unit should be evaluated over a period of at least one year to properly assess the combined effects of dry and wet weather flows, including seasonal variations in each. This program should also serve as a basis for establishing the nature and frequency of maintenance or other services to keep this type of sewer regulator operable.

2. It is recommended that additional larger scale model testing be performed to improve the accuracy of the performance prediction criteria, when applying these criteria to the design of sewer regulator structures with regulator inlet areas in excess of about 4 square feet.

3. It is recommended that additional design and testing be performed to improve the linearity and predictability of the flow diversion vs interceptor water level change characteristic for the no-moving-part push-pull sensor. This will be highly desirable in those applications where a network of sewer regulators is to be controlled from a central municipal command center.

4. It is recommended that study and experimentation be performed to evaluate the relative cost effectiveness of three suggested methods of construction: plastic interaction region insert; cast concrete interaction region insert using a plastic reusable mold; cast concrete insert using a disposable mold.

SECTION 2

INTRODUCTION

The Combined Sewer Overflow Problem

The general problem which has prompted this program is the pollution of natural water resources by overflows from combined sewers. According to the American Public Works Association, roughly three-fourths of all combined sewerage system overflows in the United States have their sources in combined outfalls[1]. For this reason, existing combined sewers are regarded as one of the most troublesome sources of pollution in this country today.

The problem is materially aggravated by the distribution of these combined sewerage systems. Serving more than one-fourth of the sewered populace of the country, combined sewers are especially prevalent in cities having populations in excess of 100,000. Such cities have generally been long established and their streets are underlain by such a complex of sewage, water, transportation, electric, steam and telephone lines that a separate sewer system is totally impractical. Beyond this, of course, the time, the inconvenience and particularly the cost of conversion to a separate system, even in many communities where conversion could still be considered, also render this approach unacceptable so long as any other solution is available.

For this reason, the Federal Water Pollution Control Administration is currently investigating a number of alternate approaches to the problem of reducing the substantial pollution problem of existing combined sewer installations. Among the potential solutions being examined is that of storing all overflows, either in the existing system or else in large lagoons or underground reservoirs, and providing the capability of pumping the stored waste water back into sewage treatment plants. By such means, the treatment plants can be kept operating near full capacity at all times with the combination of normal dry-weather (sanitary) flows and pump-back flows. Study programs are either now in progress or have recently been completed under FWPCA sponsorship to evaluate this type of installation for a number of cities.

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[1] "Report on Problems of Combined Sewer Facilities and Overflows, 1967," prepared by APWA under Contract No. 14-12-65, sponsored by the FWPCA.

A necessary part of the storage concept is that of regulating the flow of sewage into the treatment plant during heavy storms. Regulation is required to prevent overloading of the interceptor sewers and/or the treatment plant, itself, during heavy storm flows. Regulation also assures that 100% of the dry weather flow is diverted to the interceptor sewers, thus minimizing the required capacity and running costs of any pumpback facility and reducing the tendency for sanitary solids to be deposited in the storage reservoirs or low-use portions of the system.

Conventional regulation devices presently used in combined sewers for regulating flow to adjacent interceptors range from several types of manually-, float- or flow-operated gate valves to orifices, siphons, and a variety of weir configurations. Such devices all suffer from a reliability problem. This problem is caused by the environmental conditions which prevail in sewers and by the characteristics of the sewage, itself. High humidity coupled with acidic gases forms a corrosive atmosphere which attacks most materials not actually immersed in the liquid. The flow, itself, is both corrosive and charged with debris, including sticks, leaves, newspapers, sand, stones and other solids. The result is that the regulator devices tend to deteriorate rapidly, due to corrosion, to physical damage, or to the fouling and jamming action of debris.

The moving-part devices are especially susceptible to these types of damage. Although their performance can be excellent, such performance can be secured only through frequent, periodic and expensive preventive maintenance. Such no-moving part devices as weirs and orifices are, of course, less susceptible to damage. They suffer, however, from the fact that they are inherently very poor regulators even when operating perfectly. There is, therefore, a definite need for a simple regulator device which combines the superior reliability of no moving parts with the improved performance available from properly functioning conventional valves and gates.

The Regulator Problem

The problem of providing regulators that are accurate, reliable, and easily maintained is unfortunately a problem that has largely eluded solution thus far. There are, of course, passive regulator devices that are relatively dependable. Such devices as weirs and orifices, for example, have no moving parts and thus represent two of the more reliable methods for flow regulation.

Such devices are also relatively poor in their performance as regulators. Orifices, for example, regulate only to the extent that flow is proportional to the square root of the combined sewer head increase. Weir flow is proportional to the 3/2 power of the fluid head over the crest of the weir, for a rectangular weir installation. Other notch shapes yield other relationships between weir head and flow (e.g., a triangular notch having the apex of the triangle down allows flow proportional to the 5/2 power of weir head). Actual regulation, however, is usually in terms of combined sewer head rather than interceptor sewer level for most regulator configurations involving orifices or weirs. Hence, even if the orifices or weirs offered appropriate accuracy, they could still not regulate in terms of the required control parameter which is the level of flow in the interceptor sewer.

Other regulatory devices are available which offer substantially improved accuracy and, in some cases, capability of control in accordance with interceptor rather than combined sewer level. Fairly simple examples of such devices include float-operated gate valves and tipping gates used in small-size regulators. The former are gate valves actuated by floats measuring the flow level in the interceptor. The latter consist of gates having a pivot point below their center lines; excessive upstream flow causes them to be closed, while low flow rates permit them to fall completely open. Both of these devices could be made to regulate very well if the regulated fluid were clean and non-corrosive.

Unfortunately, the atmosphere within the sewer is typically wet and corrosive. The flow, itself, in addition to being corrosive is charged with solids ranging from fecal matter to earth, sticks, stones, leaves, rags, paper, and a whole variety of other objects. These solids produce jamming of gates and fouling of mechanisms, while corrosion results in rapid deterioration of mechanical parts. The result is that these otherwise satisfactory simple regulators have proven short-lived and unreliable in service.

Still other types of moving parts regulators have been developed for large-scale regulation. For very large sewers, electrically- or hydraulically-operated sluice gates driven by interceptor level sensor signals may be used. These large, complex and expensive installations are capable of exceptional performance as regulators. Unfortunately, they are also subject to the identical operating life and maintenance problems that plague the float-operated and tipping-gate valves. Frequent inspections and maintenance are required to keep the large devices operational. Unfortunately, the jamming or stalling of a gate during a severe storm is usually irreparable until the waters have receded to a point where the installation may be safely entered by men. Hence, although they do offer greater performance, this performance cannot be obtained reliably without costly inspection and maintenance.

The Use of Fluidics for Sewer Regulation

In seeking a regulation device or technique that combines the reliability of weirs, orifices and other no-moving-parts devices with the regulatory capability of moving-part valves, fluidics certainly appears promising.

Concerning the reliability requirement, the majority of fluidic devices have as one of their most obvious characteristics the elimination of moving mechanical parts. In effect, the fluid through its own internal flow dynamics performs those functions which normally require moving parts. As a result, most of the problems of moving parts in fluid systems are eliminated. Such problems as wear, backlash and slop, friction and binding, and the need for lubrication and seals, for example, all disappear when moving parts are absent. Replacing the moving parts are contoured flow channels constructed of materials requiring only structural integrity and chemical compatibility with the fluid involved. Hence, fluidic devices are obvious candidates for sewerage system use from the standpoint of potential reliability.

In addition to their simplicity, however, fluidic devices also offer a performance capability either duplicating or closely approximating that of conventional moving parts valves for regulation of systems where fluid flow is the principal controlled output. This occurs because most of the sensors, transducers, interface devices and activators are replaced by simple flow channels through which the fluid itself supplies control signals, feedbacks and power outputs in the form of such fundamental parameters as flow and pressure. In many applications, additional simplification is possible because the energy which provides the control signals is obtained directly from the main power source, thus eliminating any need for auxiliary energy sources. Inasmuch as sewage regulation is an example of such an application, the second criterion for considering fluidic devices as potential regulators is also obviously met.

Basic operation of the Fluidic sewer regulator as shown in Figure 1 is as follows: When the interceptor control port of the Fluidic sewer regulator is closed off, the jet stream is directed along the corresponding sidewall shown in Figure 2. In this condition the interceptor control registers a partial vacuum indicating a tendency to aspirate air as a result of the venturi effect. In this state the combined control port is open, allowing ample air to be aspirated which helps keep the jet stream attached to the interceptor sidewall. As the interceptor control is opened slightly, air is aspirated and the jet stream begins to pull away from the sidewall as shown in Figure 3. In this state some flow begins to be diverted into the combined discharge. As the interceptor control

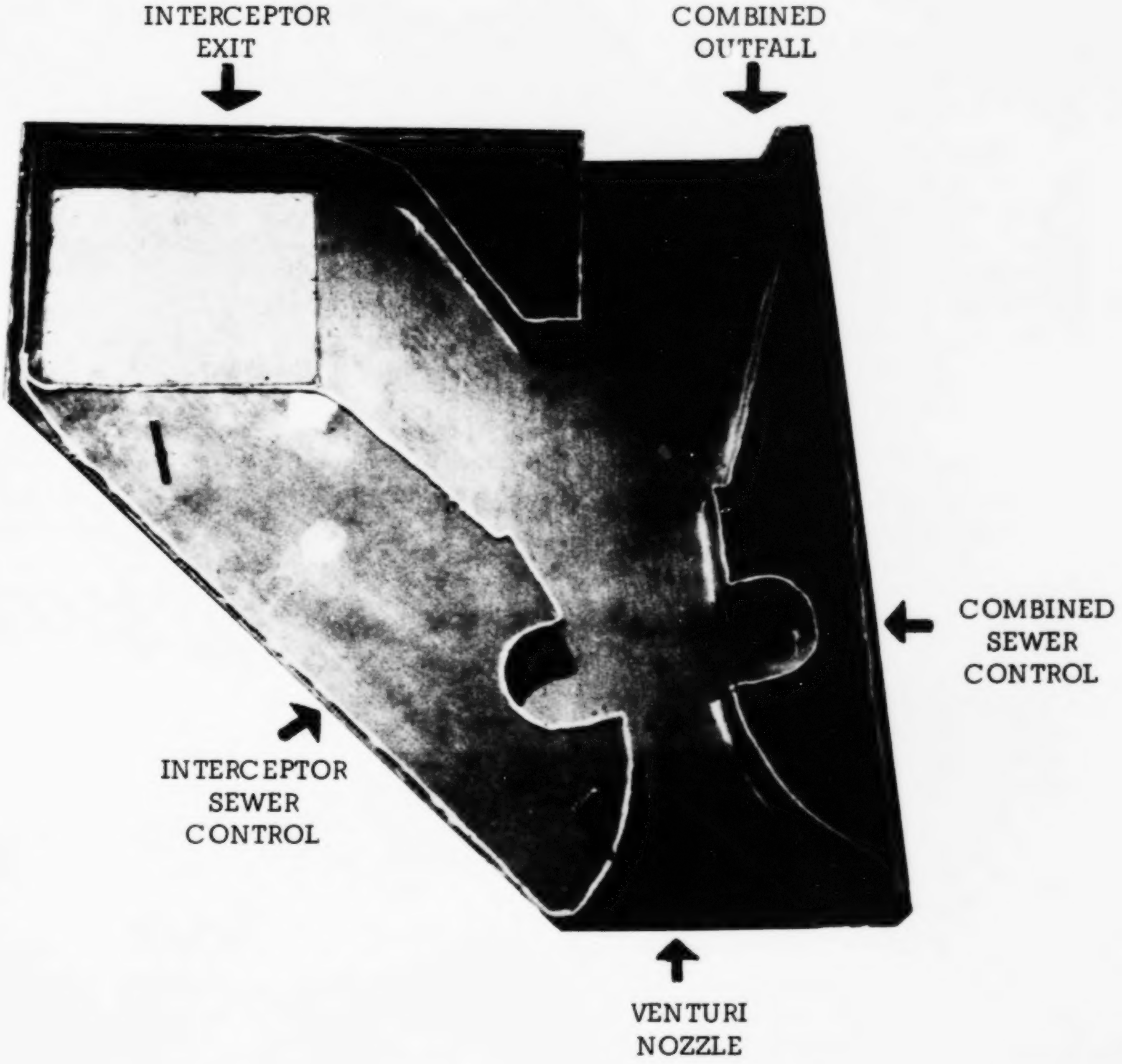
INTERCEPTOR EXIT
COMBINED OUTFALL
COMBINED SEWER CONTROL
INTERCEPTOR SEWER CONTROL
VENTURI NOZZLE

Figure 1. Final Sewer Regulator Geometry with Blunt Splitter Nozzle 2" x 4"

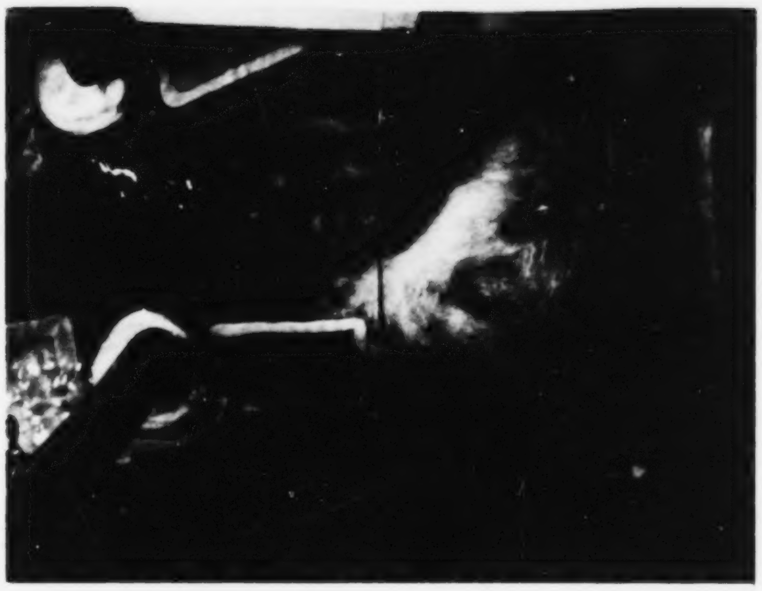

Figure 2. Fluidic Sewer Regulator Switching Action
100% Diversion to Interceptor Sewer
No Aspiration

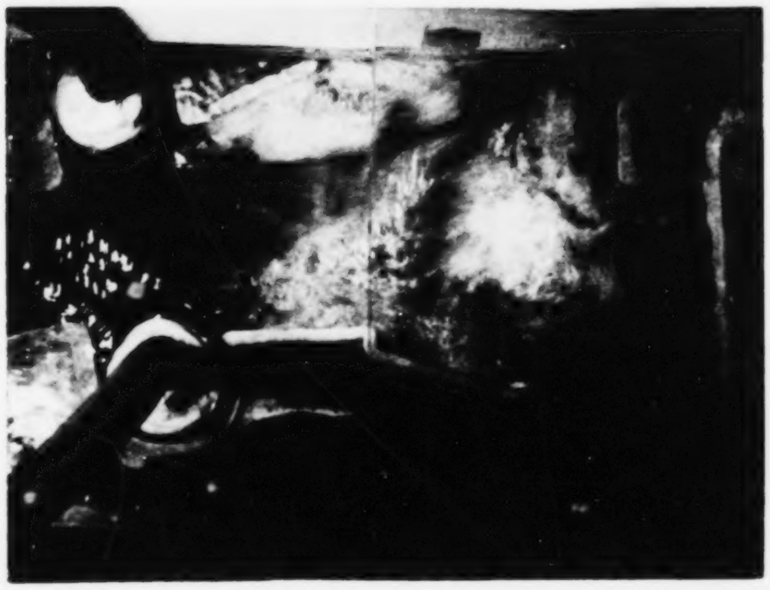

Figure 3. Fluidic Sewer Regulator Switching Action
Diversion Toward Interceptor Sewer
Slight Aspiration

is opened farther, more air is aspirated and the jet stream gradually swings away from the interceptor sidewall until it is in the center of the diverter, when the control is fully open, giving 50-50 diversion, see Figure 4. In a like manner, if the combined control is gradually closed the aspiration will be restricted and the jet stream will be drawn by the resulting pressure differential until, when the control is fully closed, almost all the flow will be directed out of the combined discharge, see Figure 5.

Fluidic devices can be considered to combine the best features of both of the two types of conventional flow regulators. They have the no-moving parts reliability of orifices and weirs. Yet they are also capable of performance and installation flexibility entirely comparable to that of servo-controlled valves or gates. Both first costs and maintenance costs can be greatly reduced, in addition, while overall operational reliability can be greatly improved.

Consider the problem of flow regulation at an existing diversion structure. The diversion structure may presently utilize as simple a regulator device as the leaping weir shown schematically in Figure 6. Conversely, it may be equipped with a completely automatic sluice gate, servo-operated, which limits flow diverted to the interceptor in accordance with the remaining capacity of the interceptor line.

Figure 7 shows a possible arrangement for a fluidic flow regulator which occupies the same diversion structure volume. The concept consists basically of embedding a fluidic flow regulator element into the weir of a conventional dammed-weir installation. One exit of the regulator leads to the interceptor portion of the installation while the other exit leads to the receiving waters. A small exit weir provided in the interceptor exit of the diverter is significantly lower than a similar weir in the combined sewer exit. Hence, normal low-velocity dry-weather flow passes through the near side of the regulator and into the interceptor line. Flow passages would be less than full under these conditions and no flow would go over the outfall weir.

The fluidic regulator is designed for control by a balance between pressures applied at control ports on either side of its intake nozzle. One of these ports, shown on the near side of the regulator in Figure 7, consists of a fixed area orifice through which air is aspirated into the flowing stream. The opposite port is shown connected to a level sensor located in the interceptor sewer. Under conditions of low interceptor flow the area through which air is aspirated from the interceptor is larger than the fixed area orifice. Hence, pressure on the far side of the flow stream is greater than that on the near side and this ΔP maintains flow

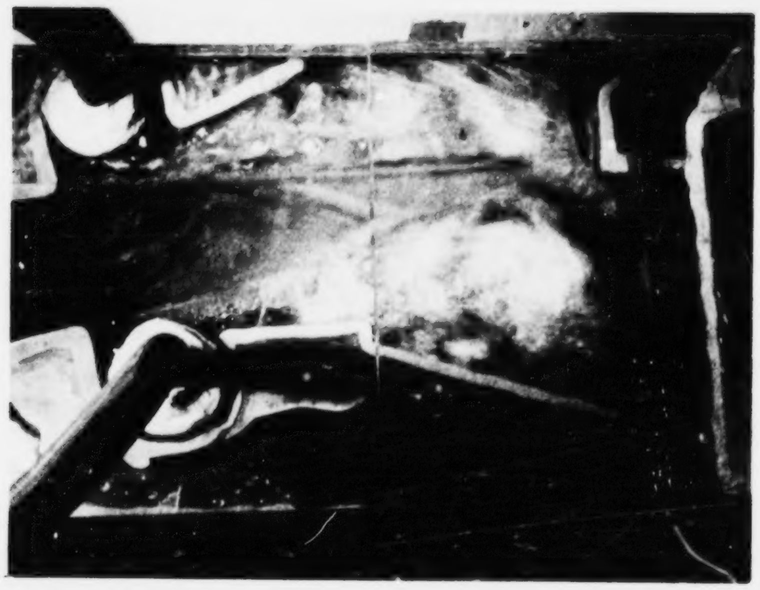

Figure 4. Fluidic Sewer Regulator Switching Action
50-50 Diversion, Aspiration at Both Controls

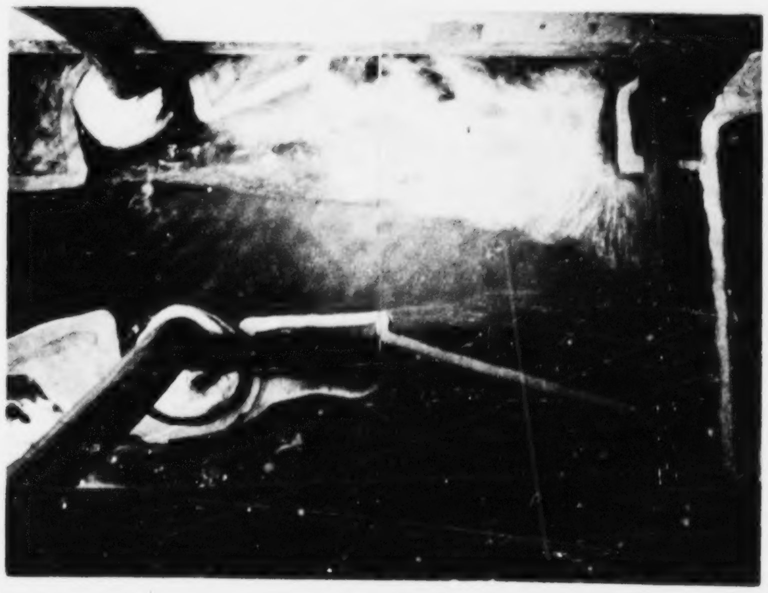

Figure 5. Fluidic Sewer Regulator Switching Action
Maximum Diversion to Combined Sewer
No Aspiration

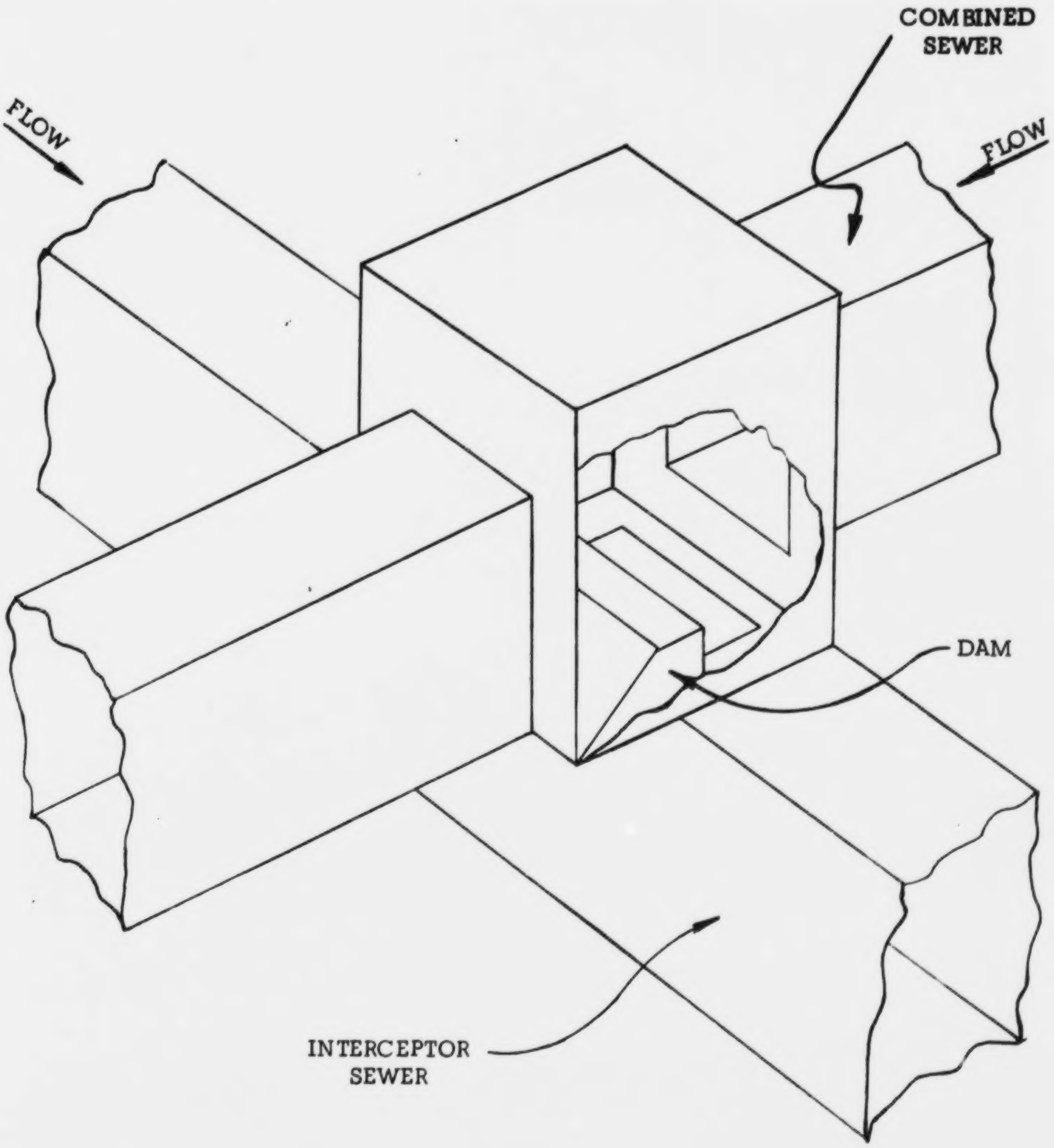
COMBINED SEWER
FLOW
FLOW
DAM
INTERCEPTOR SEWER

Figure 6. Typical Existing Diversion Structure

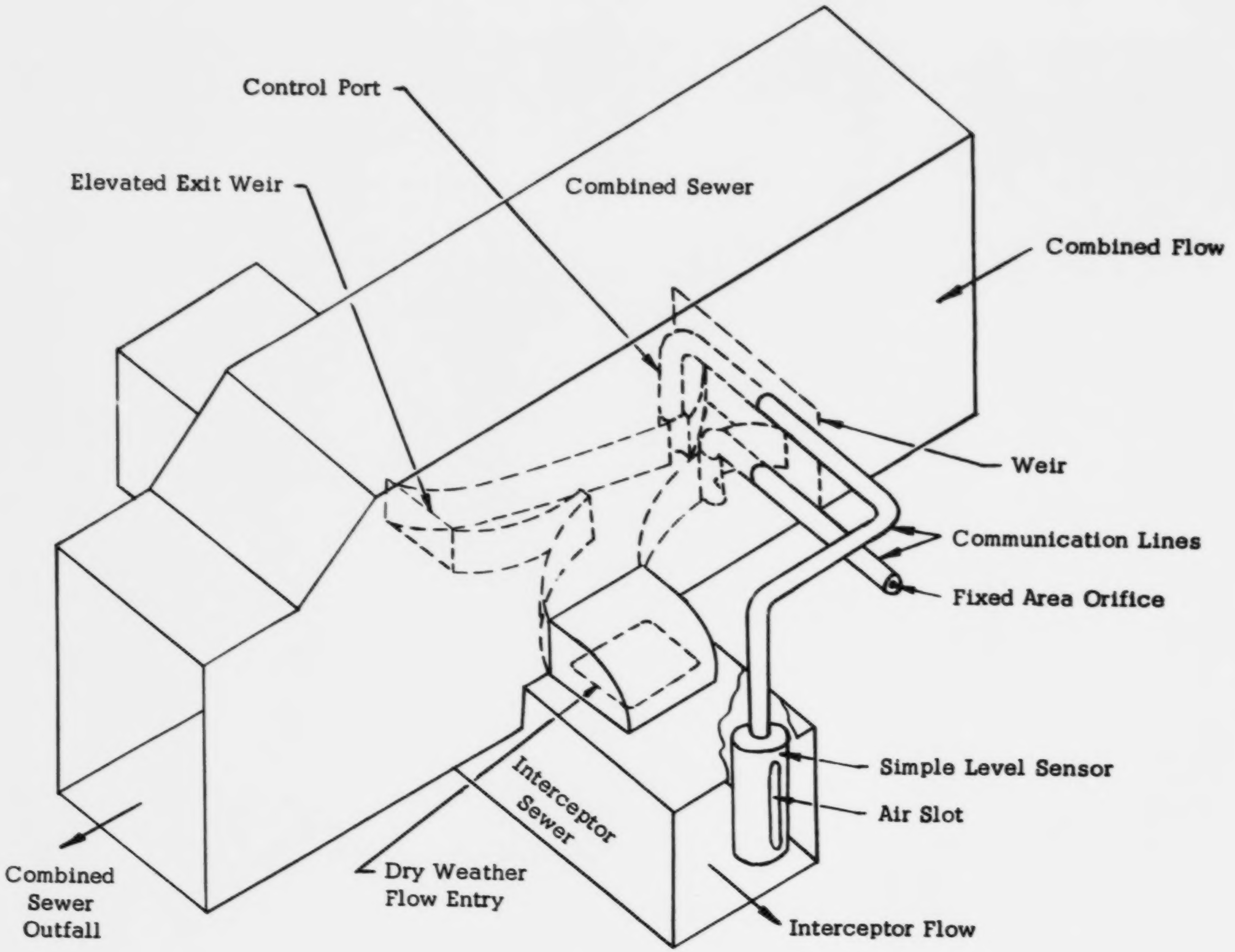
Control Port
Elevated Exit Weir
Combined Sewer
Combined Flow
Weir
Communication Lines
Fixed Area Orifice
Simple Level Sensor
Air Slot
Interceptor Sewer
Combined Sewer Outfall
Dry Weather Flow Entry
Interceptor Flow

Figure 7. Schematic Arrangement - Fluidic Sewer Regulator

into the interceptor. As interceptor flow increases, however, the aspiration area at the level sensor is reduced. This change in area produces a corresponding change in the ΔP, resulting in flow modulation to the combined sewer outfall of the regulator as the level of liquid in the interceptor sewer increases, see Figures 2 to 5.

The foregoing description of a fluidic regulator is intended primarily to illustrate the operating principles of a system utilizing such devices. Clearly, variations in geometry and size from that shown are possible. Likewise, different forms and arrangements of sensors are also possible including, for example, lead or anticipation sensors in the upstream combined sewer, and in the upstream interceptor line. One element of design which has not been discussed directly heretofore is the question of analog versus digital operation. Both types of operation are possible, of course, and the question of type is therefore best answered by simultaneously considering both the needs of the installation and the design parameters yielding a given level of performance for each type of regulator.

By nature, the properties of a fluidic regulator are a function of the geometry of its internal flow passages. The basic requirement for construction material, therefore, is simply that its geometry should be unaffected by either the operating environment or the fluid passing through it. Since this requirement is basically identical to that for the sewer, itself, it follows that the materials and techniques normally used for sewer construction should be equally applicable to fluidic sewer elements. Hence, concrete, brick and stone should be entirely adequate in most installations. The exception is in the narrow venturi section of the inlet nozzle where relatively high fluid velocities occur. In a few installations where sustained high velocity flow occurs, a local "armoring" may be necessary using a tough, smooth, non-corrosive material, such as corrosion resistant steel, high quality plastic, or fiberglass.

In the construction of these elements dimensional tolerances can be relaxed to as much as ± 5% except in the immediate vicinity of the inlet nozzle and sidewalls where a ± 2% tolerance is necessary. For reference, the latter is roughly equivalent to a tolerance of ± 1/4 inch for a one-foot nozzle width. Construction of small flow control elements can probably be done in concrete on a prefabricated basis. Large elements can either be poured directly on site or else built up of prefabricated subassemblies.

Program Approach

The technical approach for the subject sewer regulator program is based on the work conducted by the Bowles Engineering Corporation toward the development of a proprietary Fluidic automatic agricultural irrigation system. The irrigation system requirement is similar in many ways to the sewer regulator system requirement described in the previous section. Both handle relatively large water flows, operating at quite low gravity heads. Both may handle water heavily charged with solid particles, and on occasion, debris. Both are faced with significant environmental corrosion problems; both require high reiliability with a minimum of maintenance and monitoring. It is highly desirable that both systems operate without external or auxiliary energy sources, other than the main water flow, and both systems should be economical both in terms of initial and operational costs.

A schematic arrangement for a Fluidic automatic irrigation system is shown in Figure 8. This system is currently the subject of a U. S. patent application. It is under consideration by the Hawaiian Sugar Planter's Association for the automated irrigation of sugar cane, and a similar system is currently being demonstrated at the Washington State University Experimental Farm at Othello, Washington, for general automated farm irrigation as shown in Figure 9. This system will automatically irrigate a number of growing areas to the desired water depth whenever water is applied.

The system consists of a number of large fluidic diverters connected in series downslope. Water reaching the first diverter is directly initially to the adjacent growing area, then switched downslope to the next diverter. Associated with each diverter is a water level sensor, which senses a predetermined water depth in a typical furrow, and provides a signal to the diverter to switch.

In operation, each diverter acts as a digital logic flip-flop. In order to eliminate the need for positive pressure control flows, the pressure in the diverter adjacent is reduced below atmospheric ambient by narrowing the inlet nozzle in the manner of a venturi meter. Ambient air is thus aspirated into the control ports to provide control flow. In its simplest form the diverter flow is thus controlled by capping off aspirated air flow on the side of the diverter when water flow is desired, and opening the opposite side. In the case of the irrigation diverters, this arrangement is modified such that switching occurs when one control port aspirates air continuously through a small orifice, while the opposite port is either capped, or opened wide. Control flow air is allowed into the diverter through the level sensor, and interconnecting line. The level sensor consists simply of an inverted cup, whose open end is set at the desired maximum water level in the furrow. When the water level rises to the cup, air cannot enter, hence the first diverter switches its flow to the next downslope diverter. A saucer is generally placed under the cup so that the diverter will remain switched downslope if the water in the furrow recedes before all the fields have been irrigated.

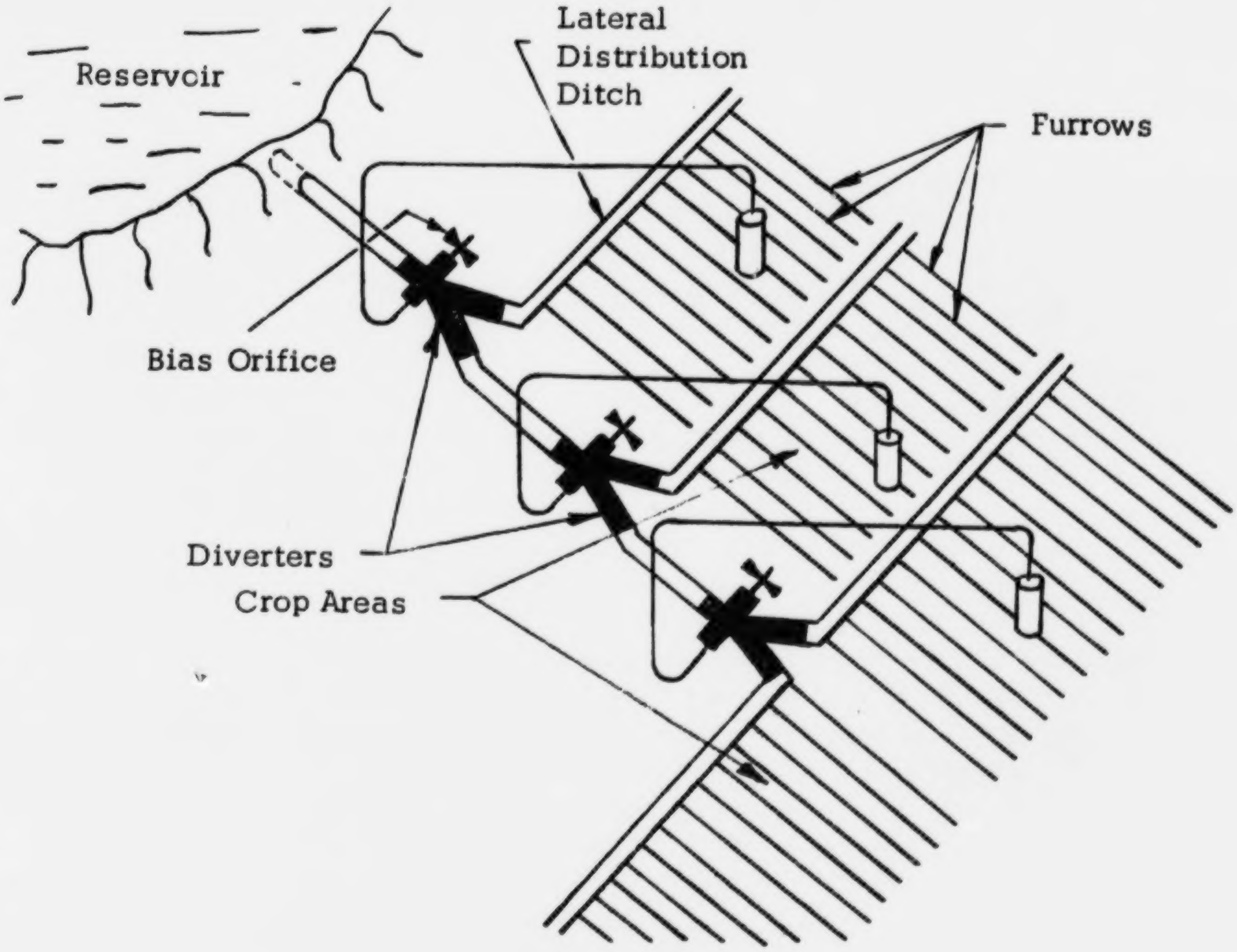
Reservoir
Lateral
Distribution
Ditch
Furrows
Bias Orifice
Diverters
Crop Areas

Figure 8. Fluidic Automated Irrigation System

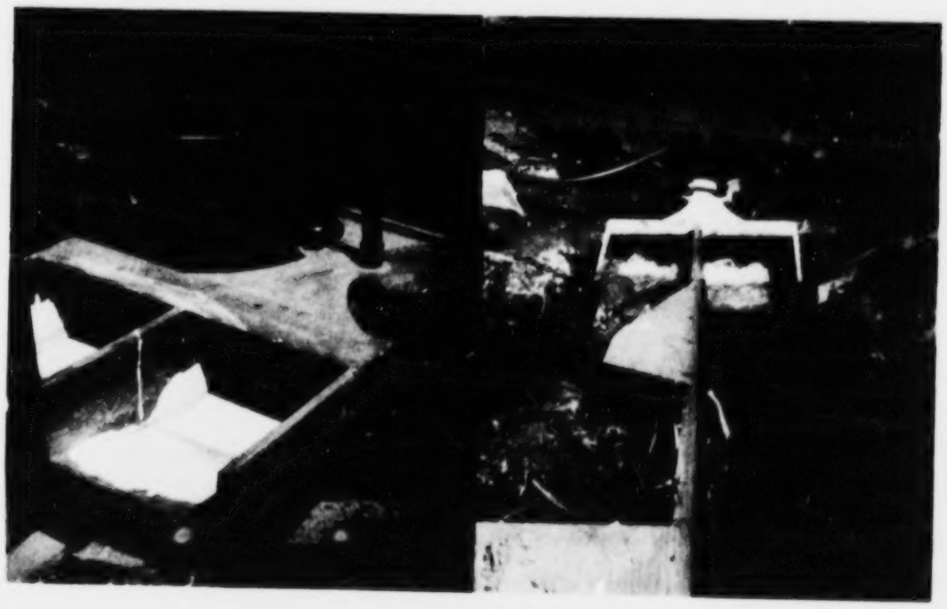

Figure 9. Fluidic Irrigation Diverter Installed at Washington State University Experimental Farm

Program Procedure

The procedure followed on the subject program has been to utilize the above described technology and practice as a starting point. Of specific use was the Fluidic element, sensor, and communication line configuration data.

The program was planned to include a number of phases: a predictive performance analysis; the construction of a test setup; the construction, testing, and evaluation of a number of experimental Fluidic Regulator models; the generation of an application design rationale for applying the test results to practical municipal design requirements; a preliminary configuration and cost analysis; and a planning and liaison effort for evaluating a full scale pilot model under operational conditions.

A major technical objective in the course of the program was the modification of a number of characteristics of the irrigation element configuration. These are described below.

The principal modification was the need for proportional flow diversion as well as the on-off, or digital type, diversion characteristic of the irrigation systems.

A second modification concerned adding the capability to operate with a considerable difference in elevation between the outlet to the interceptor, and the outlet to the receiving waters. The interceptor outlet must be lower in order that normal dry-weather, or sanitary flows, be allowed to flow with minimum impedance to the interceptor, and then onto the treatment plant. On the other hand, the outlet to the receiving waters must be elevated to prevent the dry weather flow from entering the receiving waters, except under storm flow conditions when the interceptor is running near or at its capacity.

A third modification involved the redesign of the overflow structure so that very heavy storm flows can flow over, or around the regulator without causing significant changes in its regulation performance.

Another possible modification, which is desirable for future sewer systems, is the capability for remote control from a centrally located command center. Remote regulator control is currently the subject of experiments in several large municipalities, and in time will probably be used in most large, and many smaller cities. However, due to its futuristic nature, this requirement was not investigated during the initial phases of the subject program covered by this report; nevertheless, it appears promising based on Fluidic irrigation experience.

Program Implementation and History

On February 4, 1969, the U. S. Department of Interior, through the Federal Water Pollution Control Administration, entered into a contract with the Bowles Engineering Corporation to conduct an initial research and development activity. The purpose of this activity has been to establish design and performance criteria for general application of fluidic devices to a representative range of sewer sizes and locations as a potential means for reducing or controlling combined sewer overflows.

The program was conducted under the personal supervision of Mr. Peter A. Freeman, Principal Engineer and Manager of the Water Management Group at Bowles Engineering Corporation. A total of four tasks were involved in addition to the preparation of reports. These tasks and their completion dates are summarized below:

Task I - Predictive Analysis. The purpose of this task was the analytical establishment of general design criteria for an interceptor sewer junction flow control based on fluidic technology. This task was started on February 4, 1969, and completed May 15, 1969.

Task II - Design and Fabrication of Scale Model Junction. Task II had the goal of preparing to substantiate the general design criteria developed in Task I by designing, fabricating, and assembling a scale model junction suitable for test. This task was started about February 15, 1969, and was completed May 24, 1969.

Task III - Testing. The purpose of Task III was to perform a complete series of tests of the model constructed under the preceding task. Specific objectives of the tests were as follows:

- Substantiate basic design criteria.
- Perform flow and blockage tests using both small (sand, silt and pebbles) and large (newspaper pulp, rags, confetti, lint and tree limbs) contaminants.
- Generate preliminary cost estimates for installations of various sizes.
- Test to determine the maximum practical lengths of air aspirator lines.
- Study the effects of reduction of air aspirator line cross-sectional area due to clogging or foreign material buildup.
- Determine the preferred material(s) for air aspirator lines.

This task was started on May 5, 1969, and completed September 9, 1969.

Task IV - Liaison and Planning. The purpose of Task IV was to establish liaison with one or more municipalities desiring to work toward the design and installation of an interceptor junction with a fluidic flow control. Once liaison was established, a Phase II plan covering the design of a demonstration combined sewer flow regulator installation was to be completed jointly by the cooperating municipality and BEC and included in the Phase I final engineering report. This task was started on July 8, 1969, and was completed September 3, 1969, with the agreement by the City of Philadelphia to request a FWPCA Demonstration Grant to evaluate a Fluidic Sewer Regulator.

This contract has been the first phase of a planned four-phase program. The overall program purpose is to develop, build, install and demonstrate a fluidic sewer regulator. As cited above, the purpose of the Phase I contract reported on herein has been to establish design and performance criteria on the application of fluidic devices to the problem of reducing or controlling combined sewer overflows.

Succeeding phases of the program cover respectively the design, construction and evaluation of a test system at an actual sewer site of the cooperating municipality. Phase II provides for detailed design of the test system including device design by BEC and A&E services by the municipality. Phase III covers the construction and installation of the test system. Phase IV provides for demonstration and evaluation of the test system over a twelve-month time period.

As described later in Section 6, it is expected that Phase II through IV will start early in 1970, and will continue through 1971.

SECTION 3

APPLICATION OF FLUIDIC REGULATORS

The intent of this section is to discuss the application of Fluidic Regulators to practical municipal combined sewer requirements. This section will include specific design criteria and procedures, suggested installations in typical municipal combined sewers, rough cost estimates, and suggested approaches to the maintenance and service of Fluidic Regulators.

It should be noted that the information here presented must be considered experimental and preliminary at this time. It is expected that refinements and improvements in the design and cost criteria and procedures will occur in the course of forthcoming testing to be conducted under a FWPCA Demonstration Grant.

Water Channel Sizing

The principal parameter affecting the water channel size is the maximum desired flow into the diversion channel from the combined sewer, before flow begins to bypass (over or around) the diversion structure. Also to be determined is the desired inlet head at which this flow occurs. The inlet head is established by the weir or dam height at the regulator inlet nozzle. The inlet nozzle area is computed, using the nomograph shown in Figure 10. (Note that the discharge coefficient, C_D, is a function of the relative magnitude of the inlet head as compared to the nozzle height. This relationship is shown in Figure 11. For first approximation purposes, a value of 1.0 is suggested.)

When the nozzle area, A_N, is determined, the values of nozzle height and width must be chosen, so that the best overall diversion performance can be realized. A number of considerations affect this choice.

1. Based on the program test results, a greater range of flow diversion is obtained with higher aspect ratio nozzles; i.e., h_n* large compared with w_n*. Note that flow diversion represents that part of the flow which does not enter the interceptor.

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*h_n is the height of the regulator supply nozzle.
w_n is the width of the regulator supply nozzle.

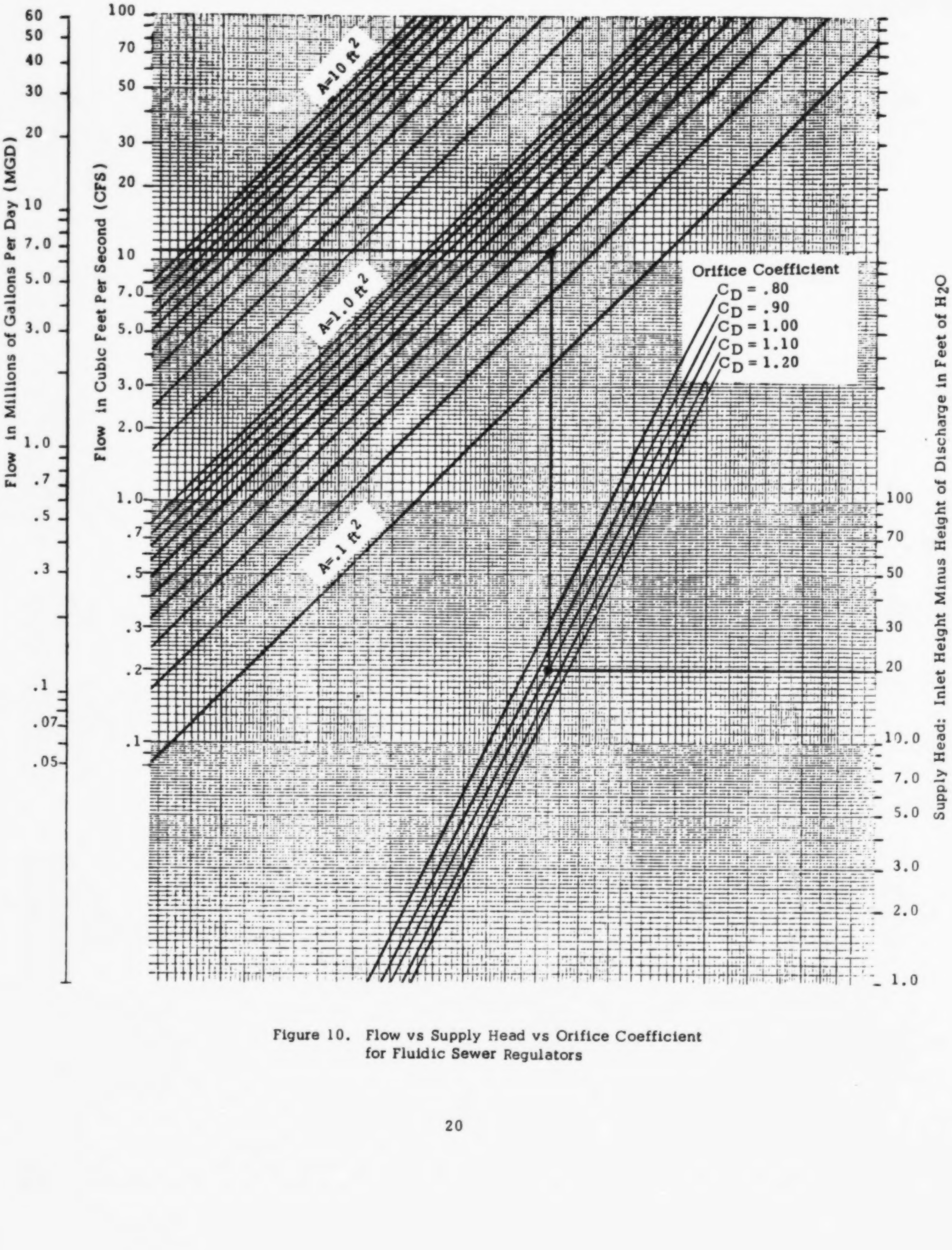


Figure 10. Flow vs Supply Head vs Orifice Coefficient for Fluidic Sewer Regulators

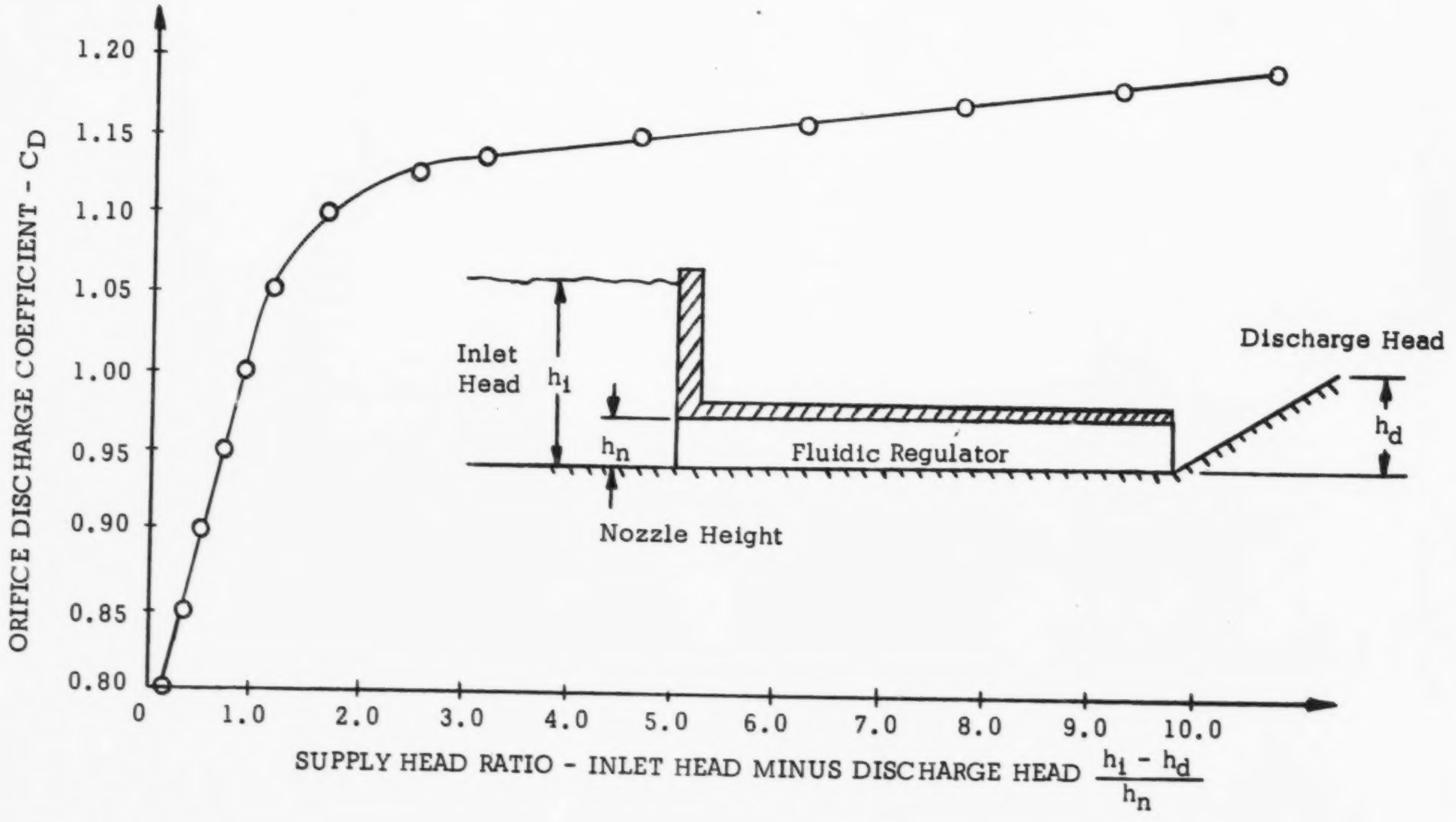


Figure 11. Discharge Coefficient vs Supply Head for Fluidic Regulators

2. Flow diversion is also strongly affected by the ratio of inlet water head to h_n. For ratios less than about 2, the range of flow diversion drops off sharply.

3. A limiting value of undiverted flow must be determined from the interceptor sewer flow handling capabilities, in that the interceptor must be able to accept this amount of undiverted flow when the combined sewer is running full. If the interceptor cannot accept this amount of flow, then the regulator inlet nozzle area must be reduced, or the nozzle weir lowered.

It can be seen that the achievement of the best diversion characteristics within the above indicated restraints may require several "trial" designs. When w_n is established, then the horizontal plane geometry of the regulator can be established, using w_n-based parameters shown in Figure 12. Note that considerable flexibility is possible in the configuring of both flow passages from a point downstream of the splitter to the interceptor inlet orifice, or the outfall weir. A good working value of the outfall weir height has been determined as (1.4) h_n. A good working value of the interceptor orifice width has been determined as 1.4 w_n, assuming a vertical dimension of h_n.

Air Channel Sizing

Two procedures for air channel sizing can be used, depending on the mode of regulation desired. Digital, or "on-off" action similar to that used in irrigation systems, can be obtained with a small fixed bias air orifice on the interceptor side; a larger fixed orifice will produce a hybrid type of action in which a limited degree of proportional diversion occurs in the vicinity of the maximum diversion range (toward the outfall). Below this range maximum flow into the interceptor occurs. Complete analog action requires a variable bias orifice, such as the push-pull sensor arrangement described later. Considerations for sizing air channels for both modes of operation are described below.

1. Digital Action. The bias orifice (interceptor side) should have an opening equal to .0015 A_N, where A_N is the nozzle area. The sensor orifice area should be .004 A_N.

The communication lines should be sized so that they produce less than 10% of the pressure drop across either the bias, or control orifices, when each is passing maximum airflow. As a guide to sizing these lines, the static pressure at the bias port when the regulator is switched to the interceptor side is -.3h, where h is the water head at the inlet. (This is the maximum airflow condition.) Also the static

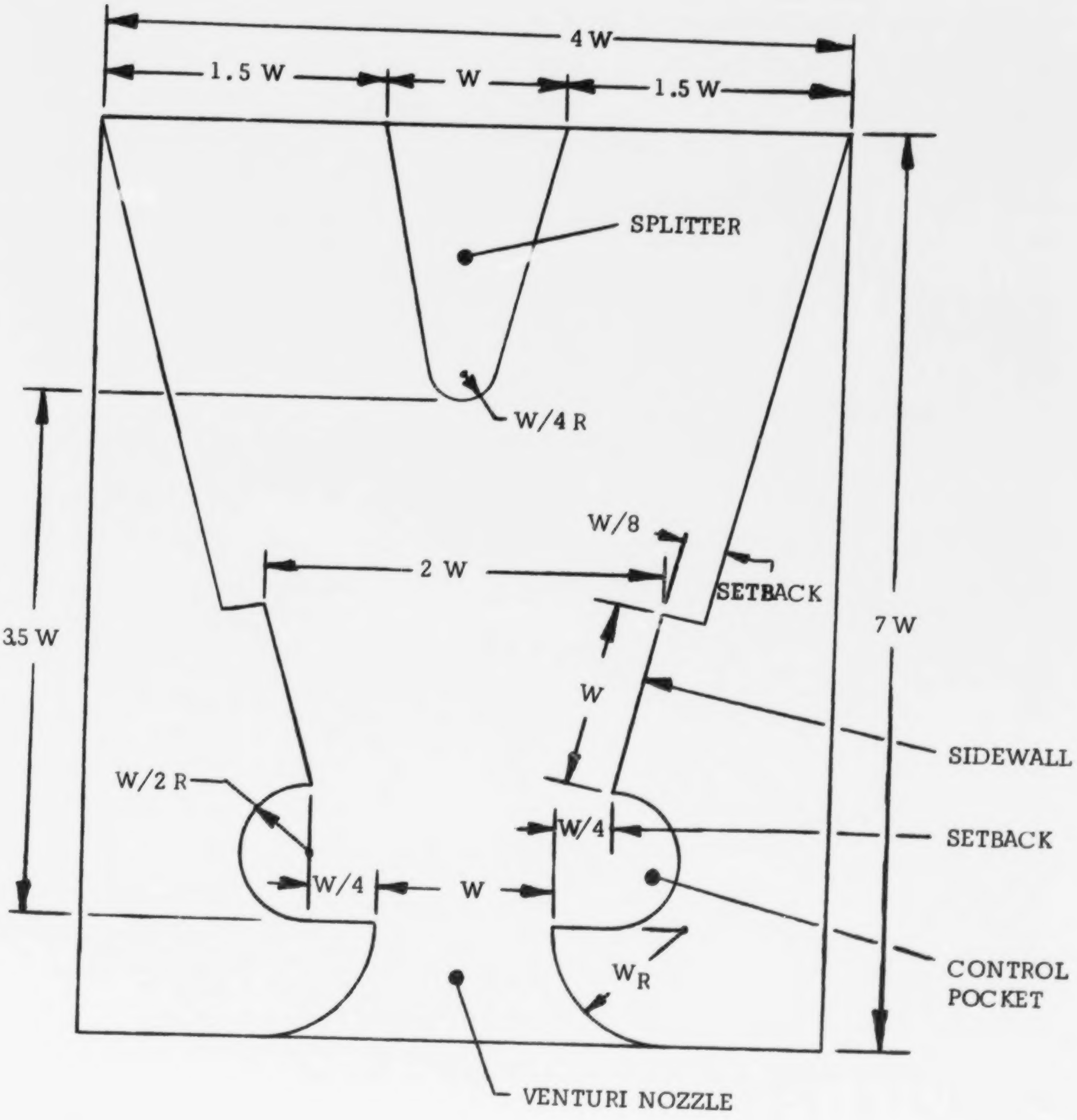

4 W
1.5 W
W
1.5 W
SPLITTER
W/4 R
3.5 W
7 W
W/8
2 W
SETBACK
W
SIDEWALL
W/2 R
W/4
W/4
W
SETBACK
CONTROL POCKET
W_R
VENTURI NOZZLE

Figure 12. Fluidic Sewer Regulator Geometry Dimensions

pressure at the control port under the same conditions is about -.1h the water head at the inlet. This also corresponds to a maximum steady airflow condition.

In a practical installation, the control orifice should be located well above the interceptor sewer water line, so that sewage cannot be drawn or "percolated" into it when the regulator is operating at high head conditions.

2. Analog Action. For analog operation, the push-pull control arrangement is recommended. The dip tube sensor located in the interceptor sewer should have a maximum orifice area = .02 A_N. The orifice should be shaped in the form of a vertical slot, or alternately, a series of holes. The vertical distribution of the orifice area is a function of range of interceptor water level over which flow regulation is desired. Experiment has shown that a linear variation of regulator diversion with interceptor water depth will require a tapered area distribution, with the largest slot width (or hole diameters) at the bottom of the dip tube.

In the experiments to date, a linear taper of the orifice slot has been used. This has resulted in a rather non-linear diversion vs water depth calibration, however. The reason for this is attributed to the fact that the fluidic element's capability to aspirate airflow into a control port drops off sharply as the main flow stream is diverted away from that side of the element; thus, a relatively large decrease in area of the control side sensor was necessary to produce a significant lowering of pressure in that part, which would allow flow to start entering the bias port. It is expected that a non-linear tapered slot, which widens sharply near the bottom of water depth range, can be formulated to produce a much improved degree of linearity. Such a contour could be formed by the area between a vertical line and a parabola. This can be described by the formula:

$$w_s = a \left(1 - \sqrt{\frac{h_s}{D}}\right)$$

where w_s = sensor slot width along contour
a = slot width at the lower water level limit
h_s = slot height along contour
D = maximum depth of slot

by simple integration, the area of the slot can be shown to be = 1/3 Da. Additional testing will be required to fully evaluate the above or other improved linearity contours.

A second dip tube sensor is required in the open side of the push-pull controller. Its orifice should be constructed with the same distribution of area as a function of variation in liquid depth, except that the depth will be determined by the maximum control pressure difference expected, the density of the controller liquid, and the relative cross section areas of the open and closed sides. The most desirable choice of the controller liquid is still open to experimentation. It appears that the most significant requirements for the liquid are good chemical stability, relatively low vapor pressure, low toxicity, and low surface tension and/or viscosity. These requirements reflect the fact the liquid must evaporate at a minimum rate; and when the regulator is called on to operate, the ambient air can bubble through it with minimum restraint, foaming, or chemical reaction.

Sizing of the communication lines can be accomplished by the relationship shown in Figure 13. This graph shows the inside diameter of the line as a function of line length and inlet nozzle area. In general, pressure drops along the communication line of a Fluidic regulator operating in the analog mode will cause errors in the desired degree of diversion. The maximum error will occur at the maximum airflow condition which has been shown to occur near the 50% diversion point. In formulating Figure 13, a maximum allowable error in diversion of 10% has been assumed as a function of increased flow impedance from the sensor orifice. The curves show the trade off of line I.D. (I.D. = inside diameter) vs length, in order to remain within the tolerable impedance increase limit. These relationships hold for variations in inlet head (assuming a maximum value of discharge coefficient, C_D).

It is recommended that all dip tube sensors be relatively large in diameter, as compared to the communication lines, to minimize the chance of "percolating" sewage, or controller liquid into the communication lines. It is recommended that communication lines and sensors be constructed from plastic pipe, in view of the very low operating pressures, need for corrosion resistance, and low cost. It appears that several types of plastic material would be equally satisfactory, including PVC, ABS, PE, or possibly polypropylene. The sensor installations in the interceptor (or combined) sewer should provide for deflectors to prevent occlusion of the orifice slot by soft debris such as rags or newspapers. A preferred location would be against a sidewall as shown in Figure 14. If a sidewall installation is otherwise unsuitable, a midflow installation could be made per Figure 15. In this arrangement, soft debris could be caught by the sensor pipe, but the side deflectors and the downstream location of the orifice slot would prevent interference with the basic level sensing function.

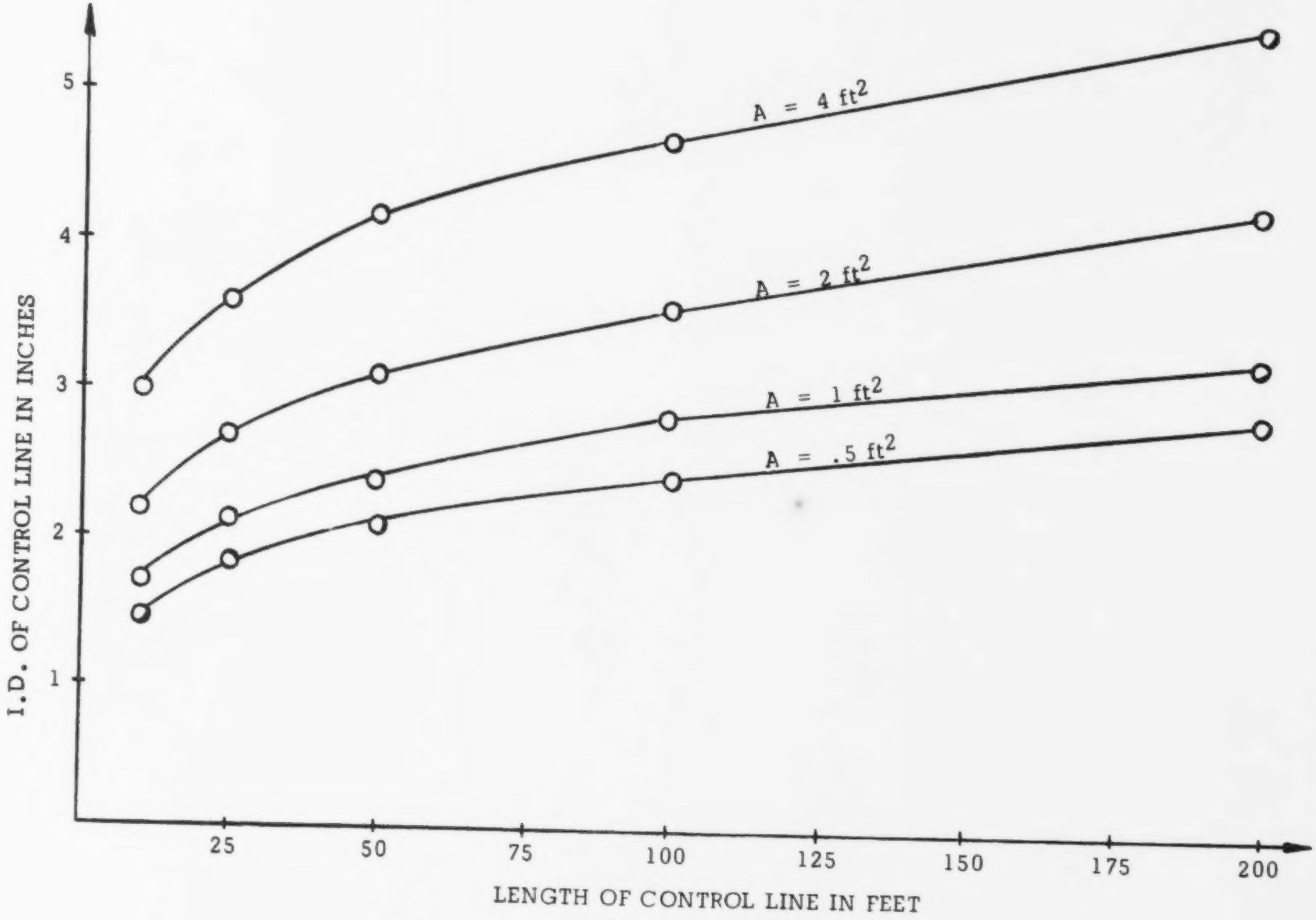


Figure 13. Control Line Diameter vs Line Length vs Nozzle Area for Fluidic Sewer Regulators

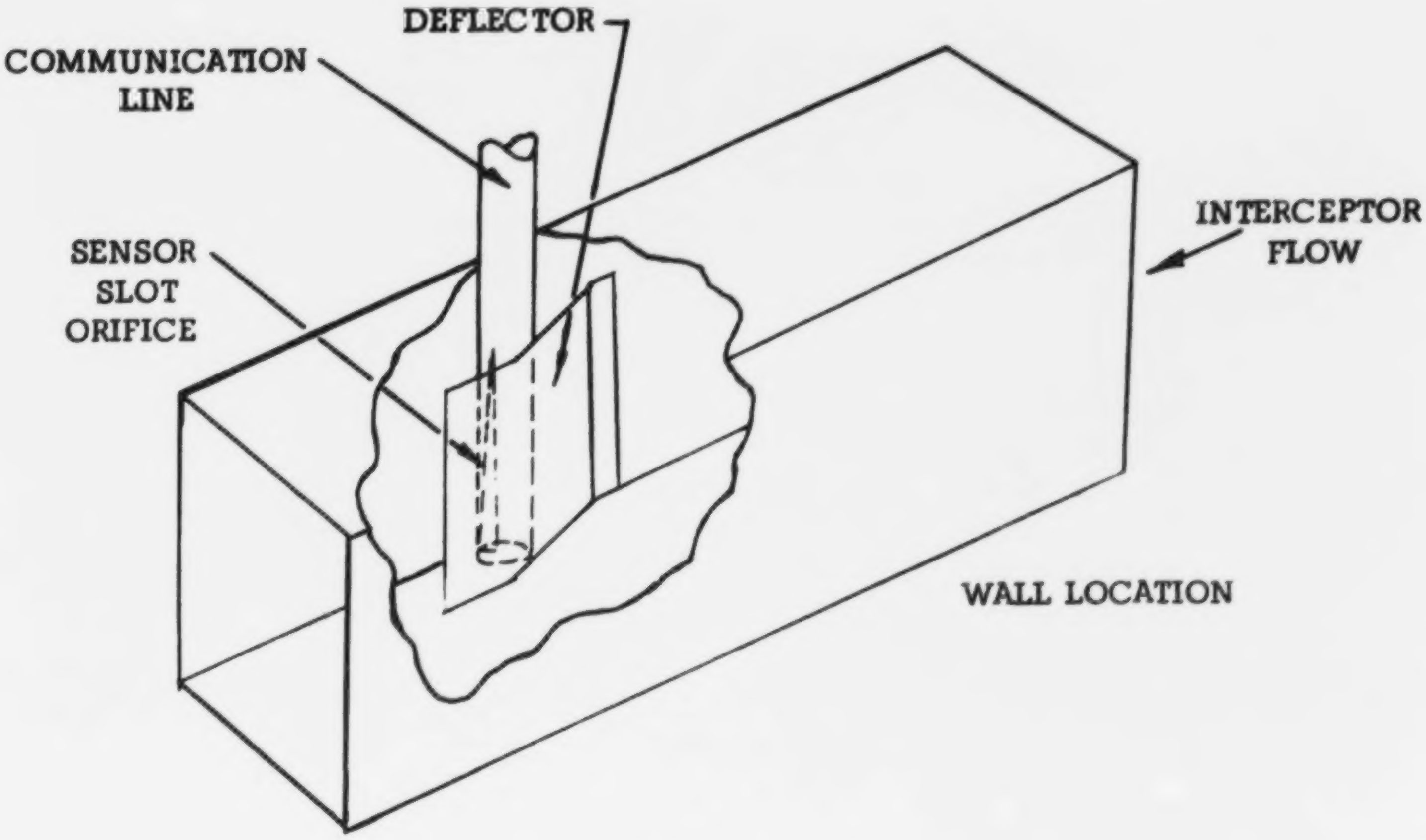

DEFLECTOR
COMMUNICATION LINE
SENSOR SLOT ORIFICE
INTERCEPTOR FLOW
WALL LOCATION

Figure 14. Sensor Installation

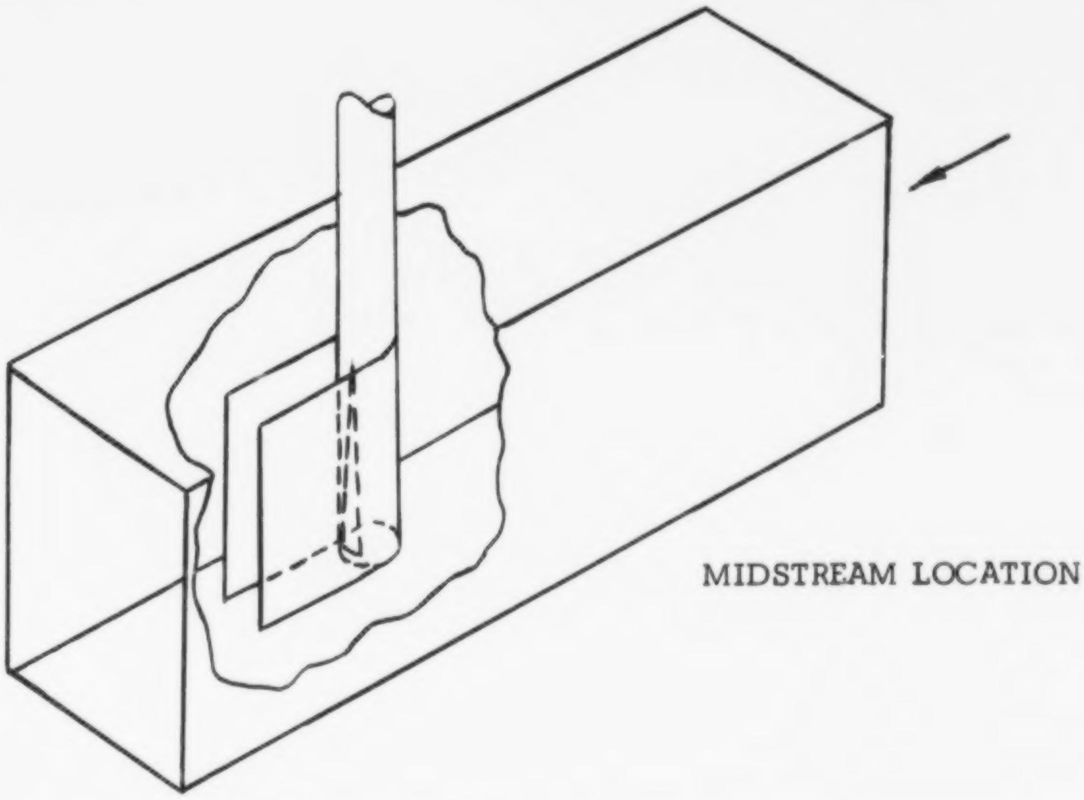

MIDSTREAM LOCATION

Figure 15. Sensor Installation

Installation

Description. In order to gain insight into the task of adapting a Fluidic Regulator into a typical municipal diversion location, construction layout drawings were obtained for several existing diversion structures in the City of Washington, D. C., and Philadelphia, Pennsylvania. These are shown in Figures 16 through 20. These structures have been modified as shown in Figures 21, 22 and 23 to outline possible arrangements and locations for Fluidic regulators, including sensors, and control equipment. In each case the sizing is only approximate, since the drawings are too limited in detail for precise scaling. The upstream weir shown is higher than that for the existing structure, since it is presumed that the Fluidic unit would be sized to handle a considerably greater flow before bypass flow would go over the regulator. This would permit a much greater flow to enter the interceptor if the latter can accept it, thereby greatly reducing the sewage flow into the receiving waters even during significant storm flows.

Construction. The construction of the Fluidic regulators is not shown in detail; however, the layouts are based on the assumption that the Fluidic element interaction region would be constructed of precast concrete shells, sealed against a concrete slab. This type of construction minimizes the likelihood of air leaking into the element interaction region. An alternate method of element construction would be the insertion of a heavy molded plastic shell of the element interaction region, secured around the edges with concrete or other masonry structure. Hard Polyethylene, or PVC, would be promising plastic materials. These units could be fabricated by rotational casting. A second alternate method would be the in-place casting of the element in concrete around a disposable core contoured to the element's internal geometry. For example, the core could be made of a plastic foam that could be easily burned away, steamed away, or dissolved away with solvents. A third alternative would be the on-site casting of the element in concrete with reusable heavy plastic molding forms. It is anticipated that the construction approach will be studied in detail during the design task to be performed as part of the Demonstration Grant activity.

Cost Estimates. At the time of writing of this report a detailed cost estimate for a complete Fluidic Regulator Structure has not been made, since such an estimate would require a detailed design for a specific site, which will not be available until the next phase of the program. The subject has been discussed with the responsible planning and construction engineers in Washington, D. C. and Philadelphia to obtain rough cost estimates of Diversion Structures with Fluidic Regulators. The following responses were obtained.

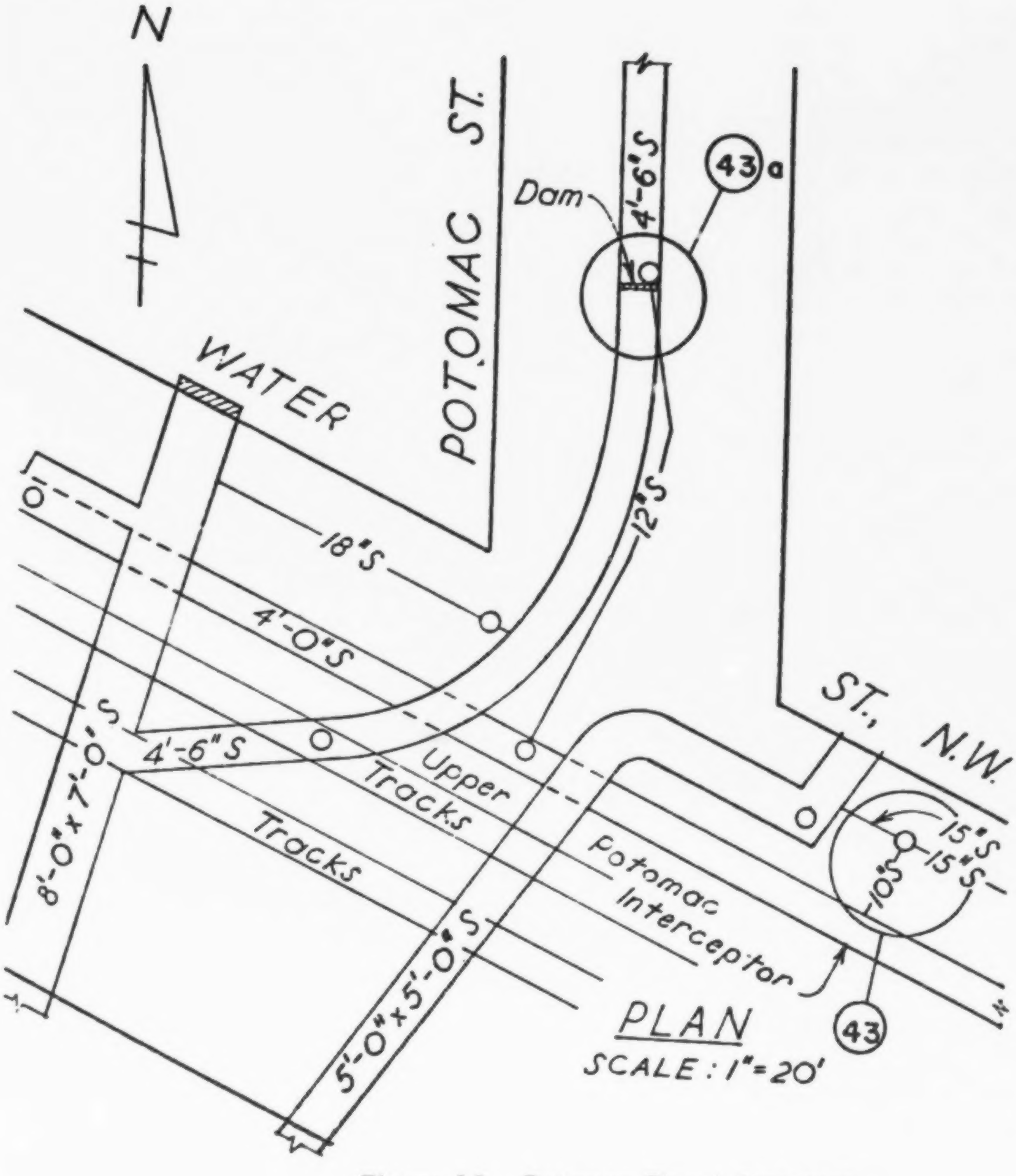
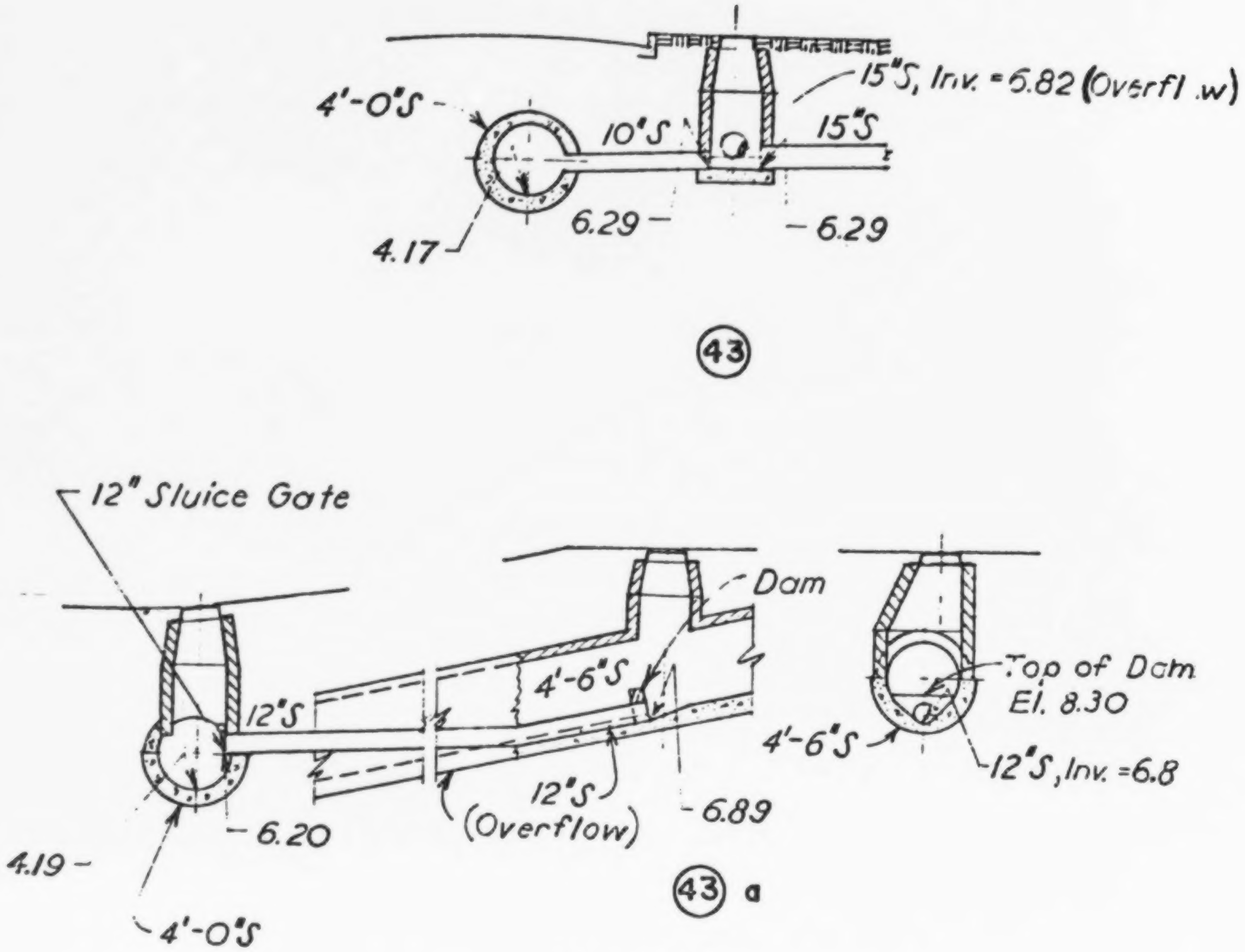
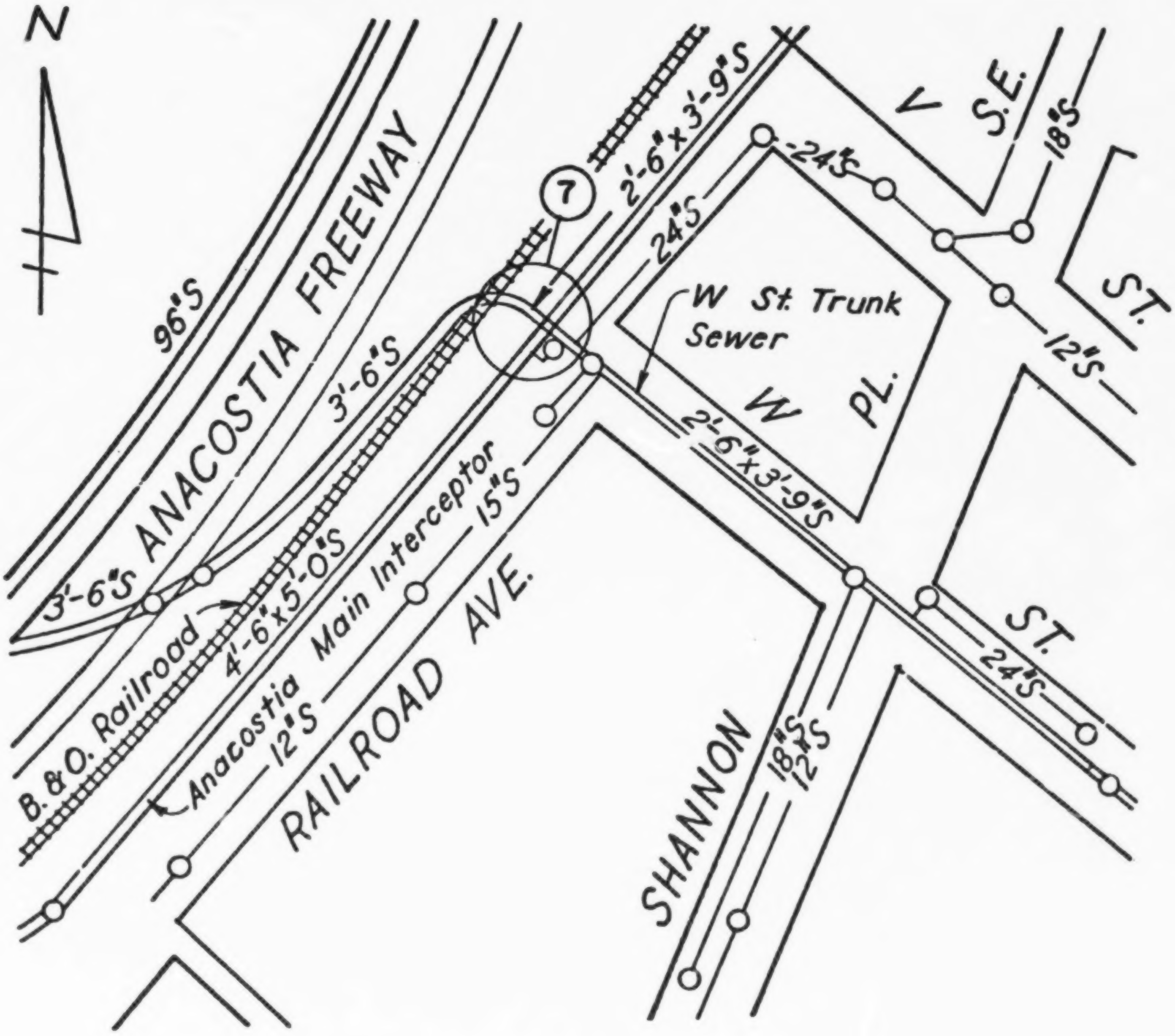

N
POTOMAC ST.
WATER
ST., N.W.
Dam
4'-6" S
43 a
43
18" S
4'-0" S
12" S
4'-6" S
Upper Tracks
Tracks
Potomac Interceptor
8'-0" x 7'-0" S
5'-0" x 5'-0" S
15" S
15" S
10" S
PLAN
SCALE: 1" = 20'

Figure 16. Potomac Street Structure
Washington, D. C.


15"S, Inv. = 6.82 (Overfl.w)
4'-0"S
10"S
15"S
6.29
6.29
4.17
43
12" Sluice Gate
Dam
4'-6"S
12"S
Top of Dam
El. 8.30
4'-6"S
12"S, Inv. = 6.8
12"S
(Overflow)
6.89
6.20
4.19
4'-0"S
43 a

DETAIL
1" = 10'-0"

Figure 17. Potomac Street Structure Details
Washington, D. C.


N
96"S
ANACOSTIA FREEWAY
3'-6"S
3'-6"S
3'-6"S
7
2'-6"x3'-9"S
24"S
-24"S
V
S.E.
18"S
ST.
12"S
W St. Trunk
Sewer
W
PL.
2'-6"x3'-9"S
B.& O. Railroad
4'-6"x5'-0"S
Anacostia Main Interceptor
15"S
12"S
RAILROAD AVE.
ST.
24"S
SHANNON
18"S
12"S

PLAN
SCALE: 1"=100'

Figure 18. Railroad Avenue Structure
Washington, D. C.

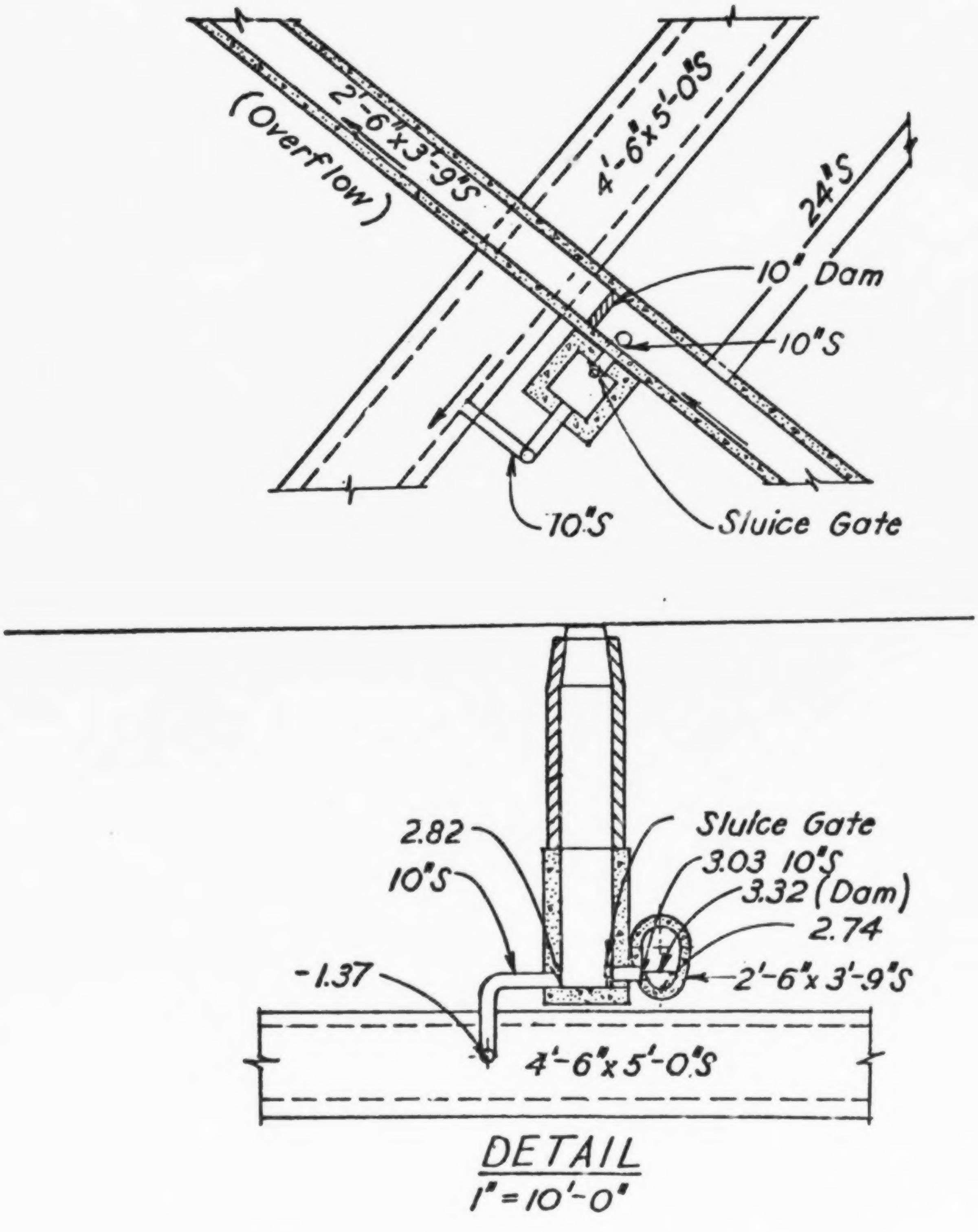

2'-6"x3'-9"S
(Overflow)
4'-6"x5'-0"S
24"S
10" Dam
10"S
10"S
Sluice Gate
2.82
10"S
Sluice Gate
3.03 10"S
3.32 (Dam)
2.74
-1.37
2'-6"x 3'-9"S
4'-6"x 5'-0"S
DETAIL
1" = 10'-0"

Figure 19. Railroad Avenue Structure Details
Washington, D. C.

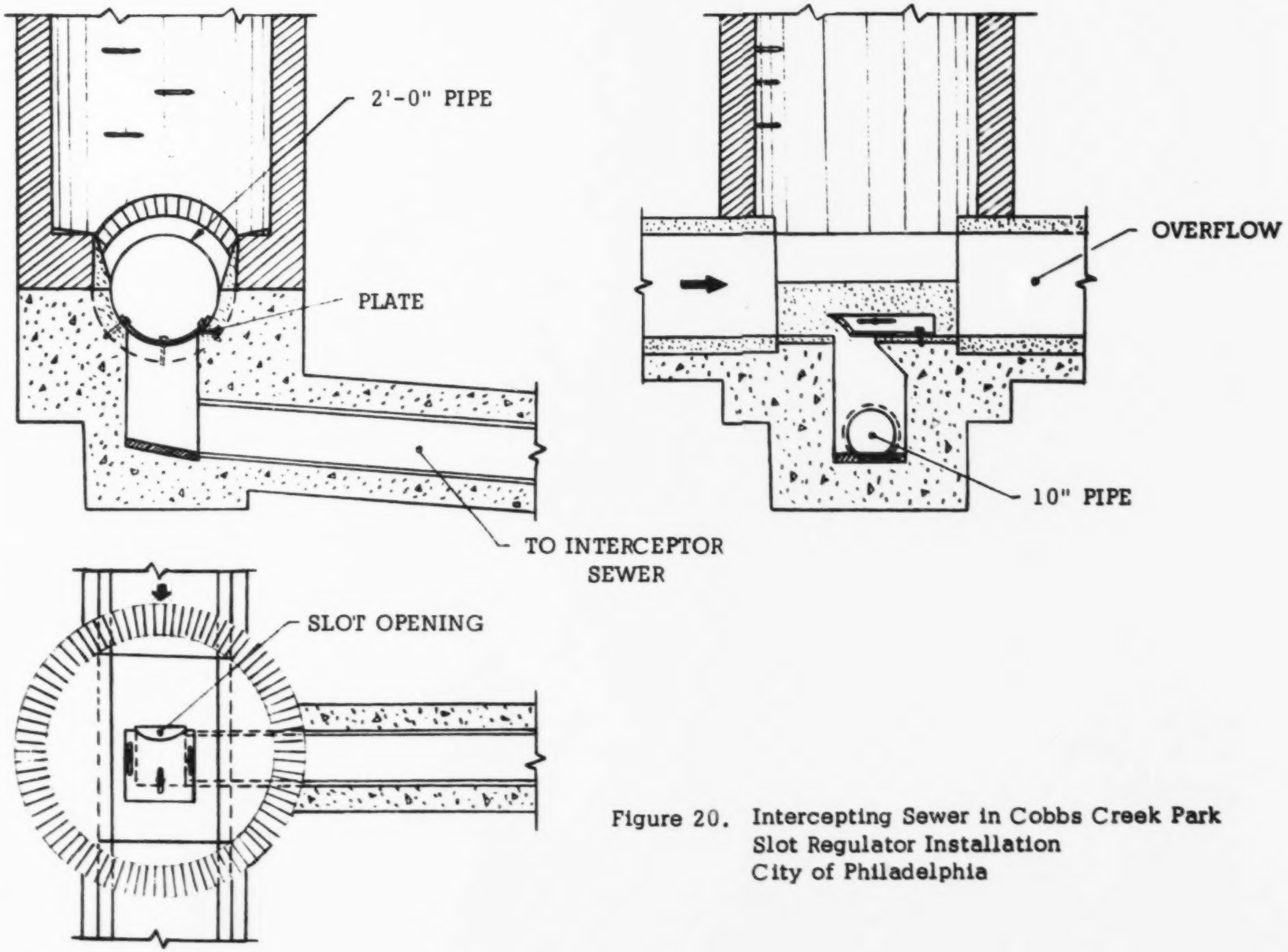

2'-0" PIPE
PLATE
TO INTERCEPTOR SEWER
SLOT OPENING
OVERFLOW
10" PIPE

Figure 20. Intercepting Sewer in Cobbs Creek Park
Slot Regulator Installation
City of Philadelphia

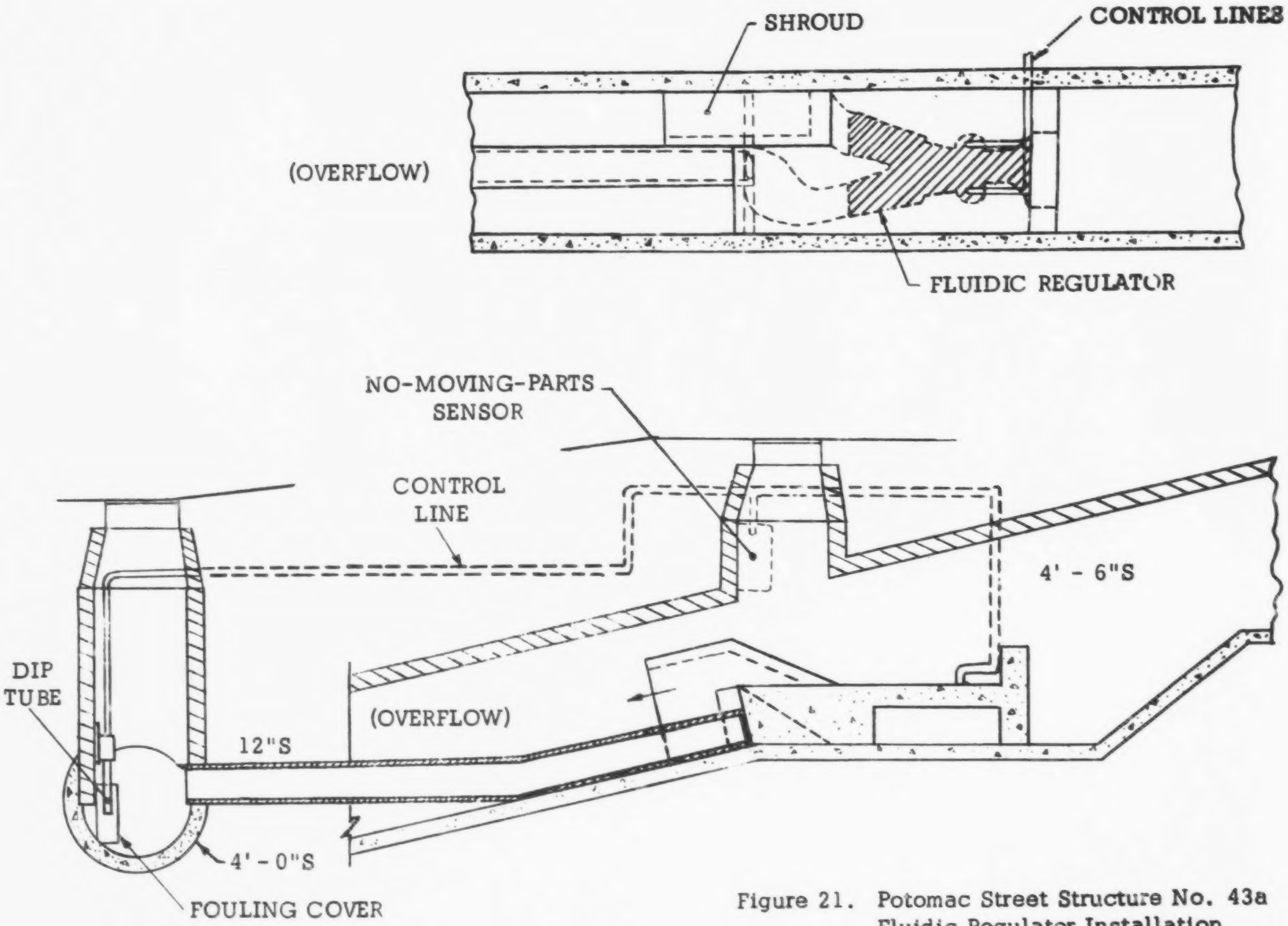

SHROUD
CONTROL LINES
(OVERFLOW)
FLUIDIC REGULATOR
NO-MOVING-PARTS SENSOR
CONTROL LINE
4' - 6"S
DIP TUBE
(OVERFLOW)
12"S
4' - 0"S
FOULING COVER

Figure 21. Potomac Street Structure No. 43a
Fluidic Regulator Installation
Washington, D. C.

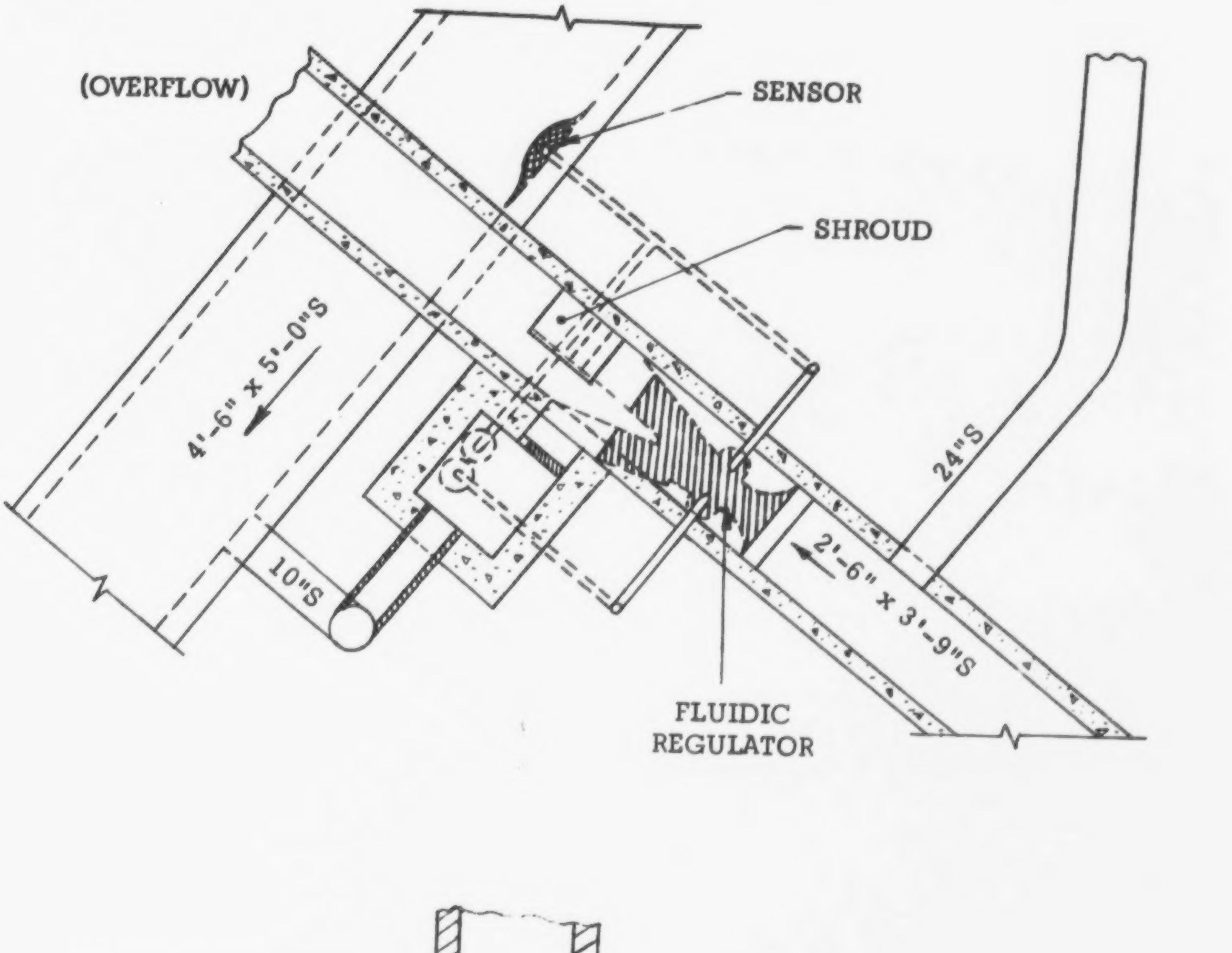

(OVERFLOW)
SENSOR
SHROUD
4'-6" x 5'-0"S
24"S
10"S
2'-6" x 3'-9"S
FLUIDIC REGULATOR
NO-MOVING-PARTS SENSOR
CONTROL LINES
INTERCEPTOR WEIR
2'-6" x 3'-9"S
DIP TUBE
REGULATOR OVERFLOW CHANNEL
10"S
FOULING COVER
4'-6" x 5'-0"S

Figure 22. Anacostia Main Interceptor Structure No. 7
Fluidic Regulator Installation, Washington, D.C.

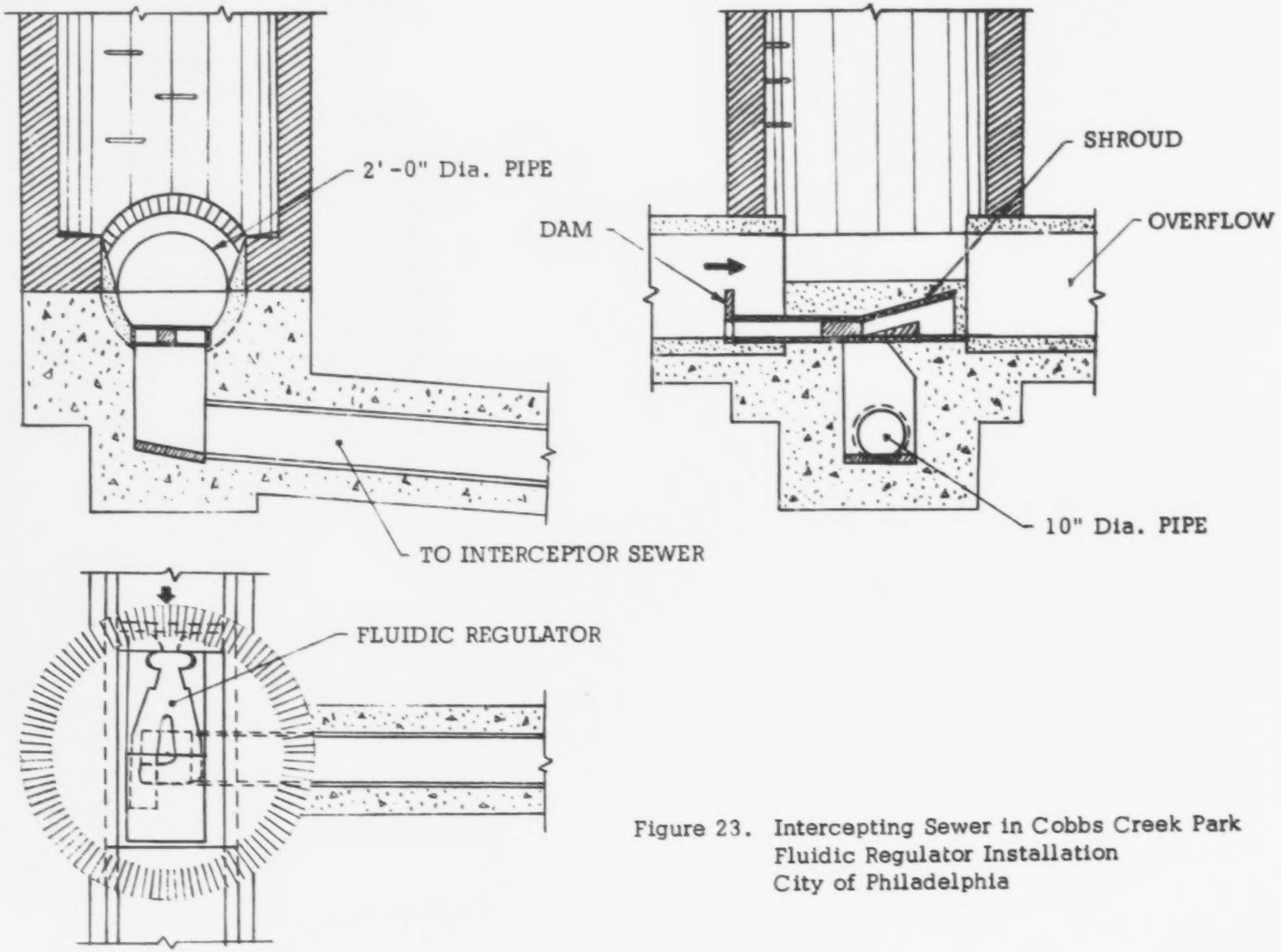

2'-0" Dia. PIPE
TO INTERCEPTOR SEWER
FLUIDIC REGULATOR
DAM
SHROUD
OVERFLOW
10" Dia. PIPE

Figure 23. Intercepting Sewer in Cobbs Creek Park
Fluidic Regulator Installation
City of Philadelphia

1. It was estimated that the cost of a diversion structure using a Fluidic Regulator would range from equivalent, to approximately 25% greater than for a conventional (weir and side pipe) diversion structure, depending on the size, and overall complexity of the structure. For a large structure, with such features as a wet well, leaping weir, elaborate manhole or other servicing access arrangements, the incorporation of a Fluidic Regulator would add a negligible fraction to the cost. For smaller structures, such as the "slot" arrangement in use in Philadelphia, a modest increase in cost would be required to incorporate a Fluidic Regulator. The initial costs of Conventional Diversion Structure costs would range from about $15,000 for the small, easily excavated installations, to over $50,000 for the larger, deeper, or more complex installations. Thus the minimum cost for a Fluidic Regulator installation might approach $20,000 while the maximum cost would not be appreciably different from current practice.

2. The City of Washington, D. C. provided a rough cost estimate for the modification of the current conventional structure shown in Figure 17 to that indicated in Figure 21. The original structure cost, at current prices, is estimated between $20,000 and $25,000. The cost of modification for a Fluidic Regulator was estimated at $15,000. In this case the modification was rather extensive, since the original sewer bottom would have to be lowered to receive the Fluidic Regulator. In contrast, for the projected modification of Figure 19, the Fluidic element could be mounted completely within the existing combined sewer walls, necessitating only a small hole for the diverted flow line. This modification could probably be accomplished for significantly less than $3,000.

3. The cost of Fluidic Regulator and auxiliaries is relatively modest. Based on cost projections for large plastic irrigation elements, a plastic insert of the element interaction region would range in cost between $50 and $150, depending on size. The cost of in-place cast concrete regulator structures is dependent on many factors such as element size, concrete costs, labor costs, etc. As an example, an element with a nozzle opening of 1' x 1.5' will contain about 12 cubic feet, assuming a 3" shell thickness. Assuming a concrete cost of $25/cubic yard, the shell material cost would be around $13. The cost of construction labor @ $4/hour would be around $20, and molding form rental would probably be on the order of $50. Thus the total cost of the installed regulator, using either type of construction, less auxiliary equipment, would be less than $100.

4. The sensor, auxiliary controls equipment, and communication lines would range in cost from $25 to $50 depending on size. This equipment would be constructed of a high grade plastic material, such as ABS, or PVC.

Service and Maintenance Procedures. Service and maintenance requirements for Fluidic Sewer Regulators should be extremely straightforward. Since there are no moving parts, there are no requirements for typical mechanism maintenance procedures, such as cleaning, lubrication, replacement of moving seals, adjustment for wear, corrosion removal, etc. The foreseeable situations requiring maintenance, or service, are described as follows:

1. Cleanout. Removable cleanout hatches would be provided in each outlet at a point abreast of the element splitter. These would facilitate the removal of very large pieces of debris, or occasional periodic flushing of accumulated solids and sediments after long periods of only dry weather flow, if necessary. (Note, experience on irrigation elements has shown that the increased flow velocity through the nozzle, even under moderate flows should minimize the sediment buildup in the element interaction region. For example, irrigation elements that have been completely "silted in" when the water is turned off, completely clear within a few seconds when the water is again turned on.)

2. Auxiliary Equipment. For those installations using the analog mode of operation, the fluid in the U-tube should be checked for level at several month intervals. For analog or digital mode operation all communication lines should be checked periodically to prevent air leakage through seals, or joints.

It may be desirable to flush, or blow out communication lines occasionally. This can be facilitated by installing fittings in easily accessible locations, and flushing with potable water, or compressed air.

SECTION 4

EXPERIMENT CONSTRUCTION AND MEASUREMENTS

Test Setup

The performance of the subject program required a test setup suitable for both the development of a satisfactory Fluidic Regulator element geometry and its evaluation under simulated system conditions. Accordingly, a test setup was designed to operate on an existing steel water test tank in the BEC laboratory. This unit is shown in Figure 24. It consists of a large wooden head tank which flows water into two closed conduits; one conduit represents a combined sewer, the other an interceptor sewer. The latter makes a 90° bend and runs across and under the combined sewer. The Fluidic element fits at the junction so that one of its outlets discharges back into the combined sewer, while the other outlet discharges into the interceptor sewer. Both sewers discharge flow into the tank, from where it is returned to the head tank through a large irrigation pump. The head tank is equipped with bypass disc valves to control water head, while the discharge from each sewer is controlled with a Bowles Engineering Corporation proprietary flexible roller curtain gate. Photographs of the completed unit are shown in Figures 25 and 26.

The test setup pump furnishes a total flow of about 1700 gpm. The pump support structure has been designed to support two additional pumps of the same type, thus giving the test setup the potential flow capacity of about 5000 gpm. With one pump, each conduit can flow about 1/2 full at a flow velocity of about 1.7 feet/sec. If a scale factor of 10:1 were assumed, a flow velocity of 17 feet/sec would be simulated. If all the available flow passes through one conduit, the simulated velocity can be doubled to 34 feet/sec, which can adequately simulate a flood flow condition.

Experimental Fluidic Element Construction

The test setup is arranged so that the experimental Fluidic element under test slides into place through the side of the combined sewer in the manner of a desk drawer for easy removal and adjustment between tests. Both combined and interceptor sewers are fitted with Plexiglas sides in the vicinity of the element for visual observation of the element performance.

The test elements were constructed of a stack of 1/2" marine plywood laminations, a plywood floor, and a Plexiglas top, through which

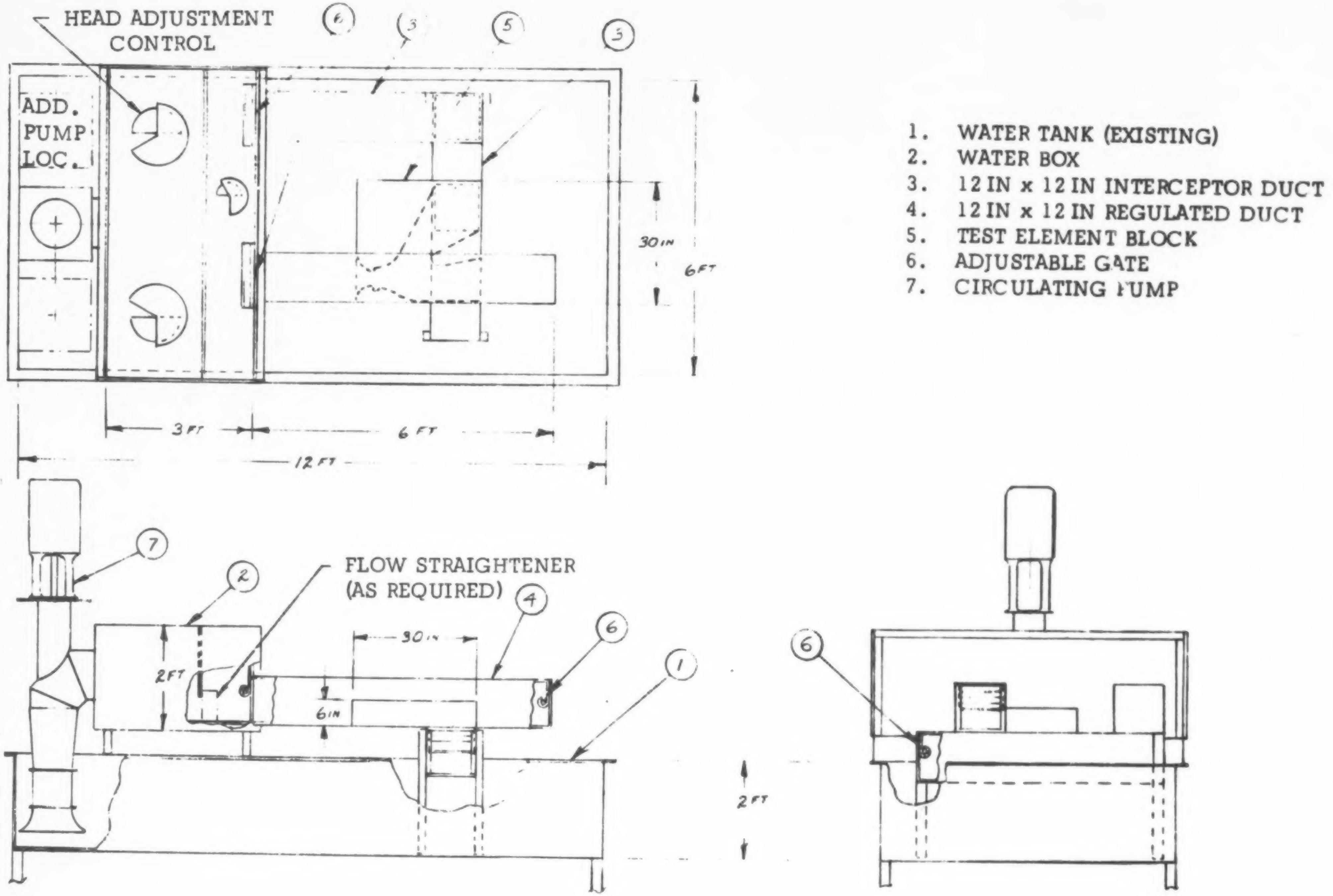

HEAD ADJUSTMENT CONTROL
6
3
5
3
ADD. PUMP LOC.
30 IN
6 FT
3 FT
6 FT
12 FT
7
2
FLOW STRAIGHTENER (AS REQUIRED)
4
6
1
30 IN
2 FT
6 IN
2 FT
6
1. WATER TANK (EXISTING)
2. WATER BOX
3. 12 IN x 12 IN INTERCEPTOR DUCT
4. 12 IN x 12 IN REGULATED DUCT
5. TEST ELEMENT BLOCK
6. ADJUSTABLE GATE
7. CIRCULATING PUMP

Figure 24. Fluidic Sewer Regulator Test Layout

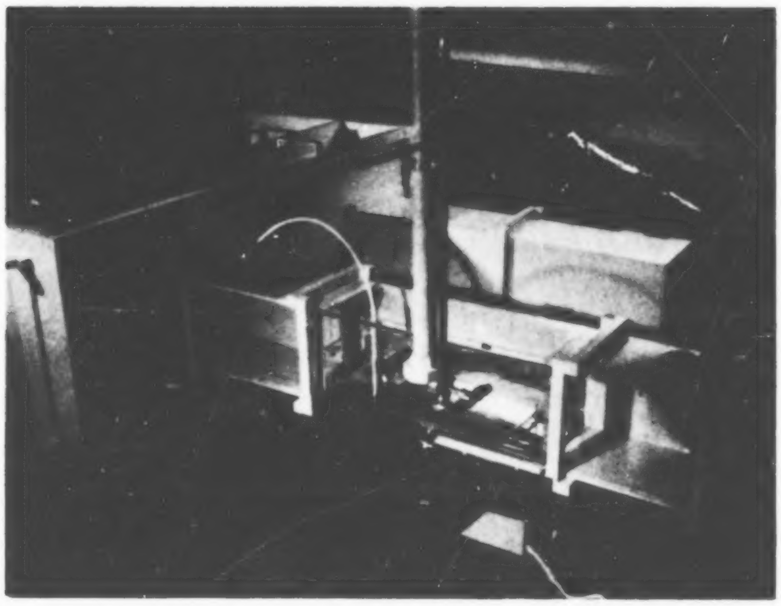


Figure 25. Test Installation Showing Head Box

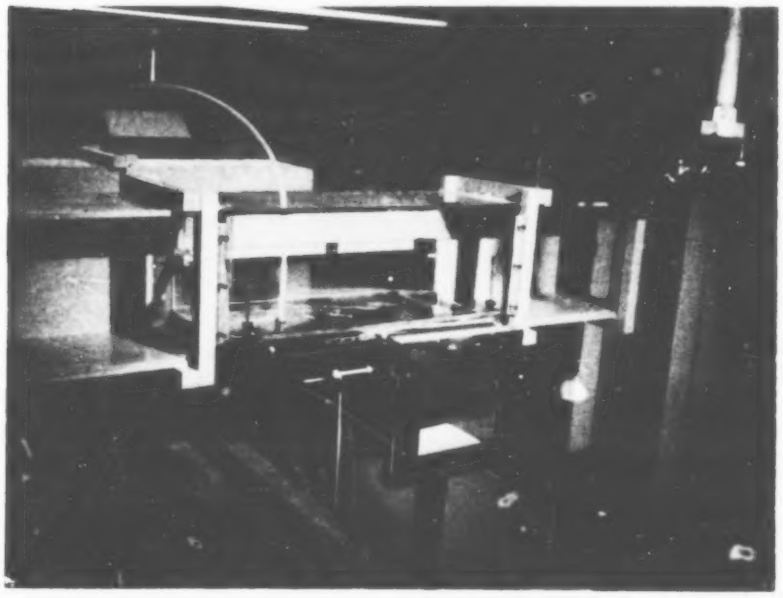


Figure 26. Test Installation Showing Sewers and Regulator Insert

the aspiration control airflow was passed. The plywood laminations were cut out to accommodate the maximum width dimensions anticipated during the test program. A "basic" maximum nozzle width of 5" was thus obtained. Element depths from 1/2" to 4" were obtained by adding or subtracting plywood laminations. The basic element test insert is shown in Figure 27. In the course of testing, internal geometry was changed by bending strips of aluminum flashing to the desired contours and anchoring these strips to the element floor and cover with strips of caulking putty.

The combined sewer discharge weir was constructed of an aluminum sheet, which was pivoted at the sewer floor to adjust the weir height. The weir was sealed along the sewer sides with putty. The interceptor discharge gate was designed initially to provide a narrow, full depth passage to pass simulated dry weather flow without any head backup. The gate height increased to full element depth along a diagonal. The gate was vertically adjusted to vary the exit area.

Measurements

Water flow measurements were made by timing the interval required to fill a 18.7 gallon bucket. This provided a measurement accuracy within 2%, except for timing intervals less than 10 seconds, where the accuracies were on the order of 5%.

Water heads and weir settings were measured directly using scales against the transparent Plexiglas sides of the test sections.

Control port pressures were measured using conventional water manometers.

Control port airflows were established by measuring the pressure differential across various sized, precision sharp edged orifice plates. An inclined manometer was used for very small differential pressure measurements.

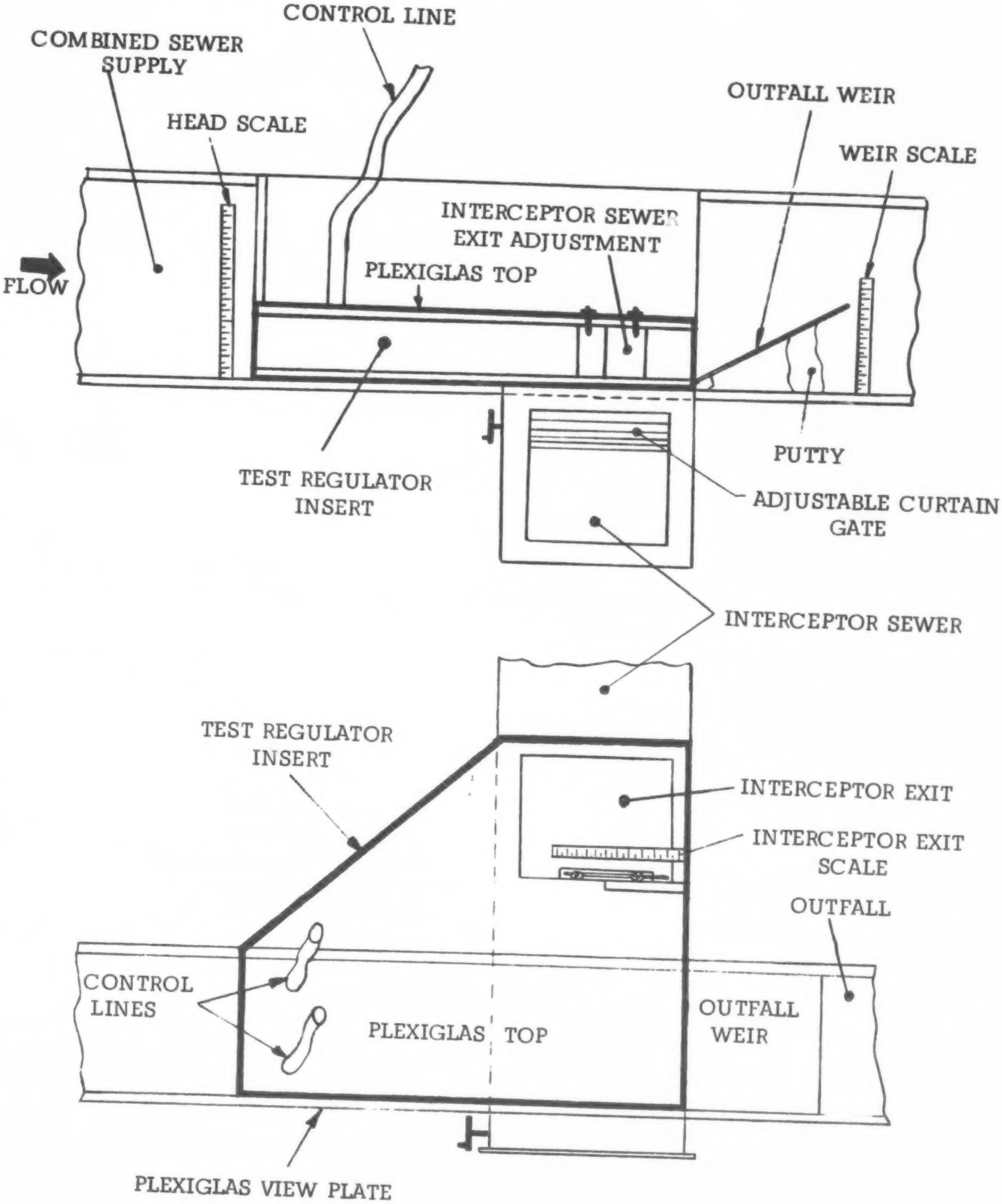

CONTROL LINE
COMBINED SEWER SUPPLY
HEAD SCALE
OUTFALL WEIR
WEIR SCALE
INTERCEPTOR SEWER EXIT ADJUSTMENT
PLEXIGLAS TOP
FLOW
TEST REGULATOR INSERT
PUTTY
ADJUSTABLE CURTAIN GATE
INTERCEPTOR SEWER
TEST REGULATOR INSERT
INTERCEPTOR EXIT
INTERCEPTOR EXIT SCALE
OUTFALL
CONTROL LINES
PLEXIGLAS TOP
OUTFALL WEIR
PLEXIGLAS VIEW PLATE

Figure 27. Fluidic Regulator Test Insert

SECTION 5

DISCUSSION

Predictive Analysis

The purpose of the predictive analysis was to obtain design criteria from the established irrigation element configuration which would provide a theoretical basis for the design of larger size model sewer regulators. It was found after an initial effort, however, that a purely analytical approach would have been prohibitive in time and cost, due to the general mathematic complexity in handling two-phase flow field phenomena. Consequently, it was decided that existing performance data available from the testing of several large irrigation diverters, plus additional data to be taken on a small diverter, could adequately provide the basis for performance predictions of fluidic sewer regulator elements.

The test setup shown in Figures 28 and 29 utilizes a 1/2" x 1/2" nozzle size irrigation diverter. Test data was taken to obtain mathematical relationships for: Flow as a function of head, diversion as a function of control orifice size, control pressure and flow as a function of diversion and head, and geometrical modifications vs analog control range. The results of the tests were graphically analyzed and compared to theoretical predictions as well as actual data taken on large scale models of the irrigation configuration. See Appendix A for log of tests.

Flow vs Head Analysis. In an effort to obtain design data to predict the flow through water regulators for a range of supply heads and nozzle sizes, flow data over a wide range of supply heads were taken for a 1/2" x 1/2" nozzle diverter as part of the task 1 testing. Additional flow vs head data were obtained from an 8" x 8" nozzle diverter from tests conducted by the Agricultural Research Service at the Engineering Research Center, Fort Collins, Colorado. The data from these two size diverters were used with the orifice equation to determine the relationship of orifice discharge coefficient to the supply head as shown in Figure 11. For the purpose of this study it was assumed that the orifice coefficient did not change with aspect ratio*; however, for aspect ratios much less than or greater than 1 this variable must be considered. See Appendix B for a discussion of the orifice equation, graphical data, and calculations of orifice coefficient. The orifice

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$$*\text{Aspect Ratio} = \frac{\text{height of supply nozzle}}{\text{width of supply nozzle}} = \frac{h_n}{w_n}$$

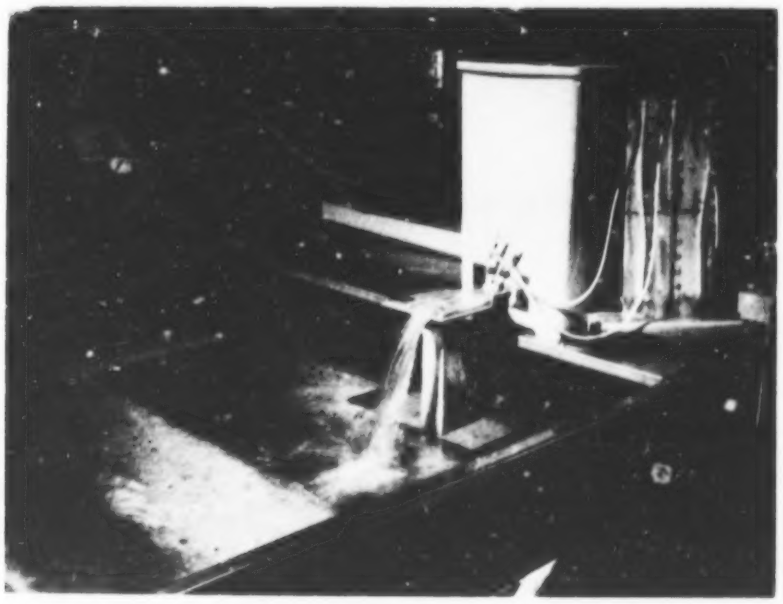


Figure 28. Fluidic Irrigation Diverter 1/2" x 1/2" Nozzle Used in Predictive Analysis Tests

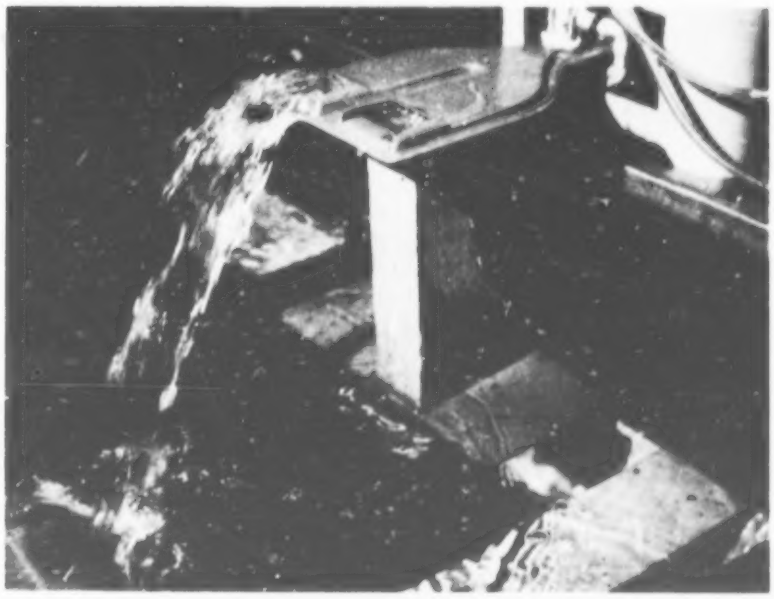


Figure 29. Fluidic Irrigation Diverter 1/2" x 1/2" Nozzle Operating at 100% Diversion

equation was then used along with the values of orifice coefficient obtained from the report of test results from the Fort Collins irrigation diverter to produce a nomograph of supply head vs flow through diverters as a function of the nozzle areas and orifice coefficients. See Figure 10. The head vs flow characteristic of the 1/2" x 1/2" irrigation diverter tested was compared to the nomograph data and was found to closely agree, even though the scale factor between the two diverters compared was over 250:1. Also, head vs flow data were obtained in testing model sewer regulators with 2" x 1", 2" x 4", and 4" x 4" nozzle sizes. A comparison with the nomograph predicted flow values showed agreement to within five (5) percent.

Testing of the small size diverter used for the predictive analysis also yielded a graph of minimum supply head vs nozzle height for 100 percent diversion performance of the diverter. Comparison of this data with the 8" x 8" Fort Collins diverter and the various size model sewer regulators tested showed good agreement. This graph is shown in Figure 30 for diverters having square nozzles, or aspect ratio 1. Although this curve applies specifically to the 100% diversion condition, it indicates the relative ability of small elements vs large elements to provide flow diversion for various head/nozzle height ratios. Accordingly, this curve is useful in interpreting experimental test results taken on small elements, on the effect of nozzle aspect ratio on diversion performance. This will be described later.

Biasing Orifices. In order to obtain scaling information for control orifice size the small 1/2" x 1/2" nozzle irrigation diverter was tested with a fixed orifice of specific diameter on one control port and a range of orifices on the opposite control as shown in Figure 31. The results of the biasing orifice testing are shown graphically in Figure 32. See Appendix C for actual data curves. Results showed that the bias orifice for maximum diversion performance had to be 0.12 (10^{-2}) A_N, where A_N = nozzle area; and the control orifice had to vary from nearly closed to ten (10) times the area or approximately three times the diameter of the bias orifice to provide maximum diversion control. The validity of this data for reliable scaling was confirmed by its agreement with the required control port sizes used on the 8" x 8" nozzle diverter tested by the Agricultural Research Service at Fort Collins. Even though bias orifice tests were performed on an irrigation configuration designed primarily for digital operation, an analog control region was observed which provided diversion control between 30 and 70 percent. See Figure 32. Bias orifice control of irrigation diverters is shown producing proportional diversion in Figure 33 and total diversion in Figure 34. The bias control data were useful in designing a dip tube sensor configuration to be used in the scale model test program and investigating analog control.

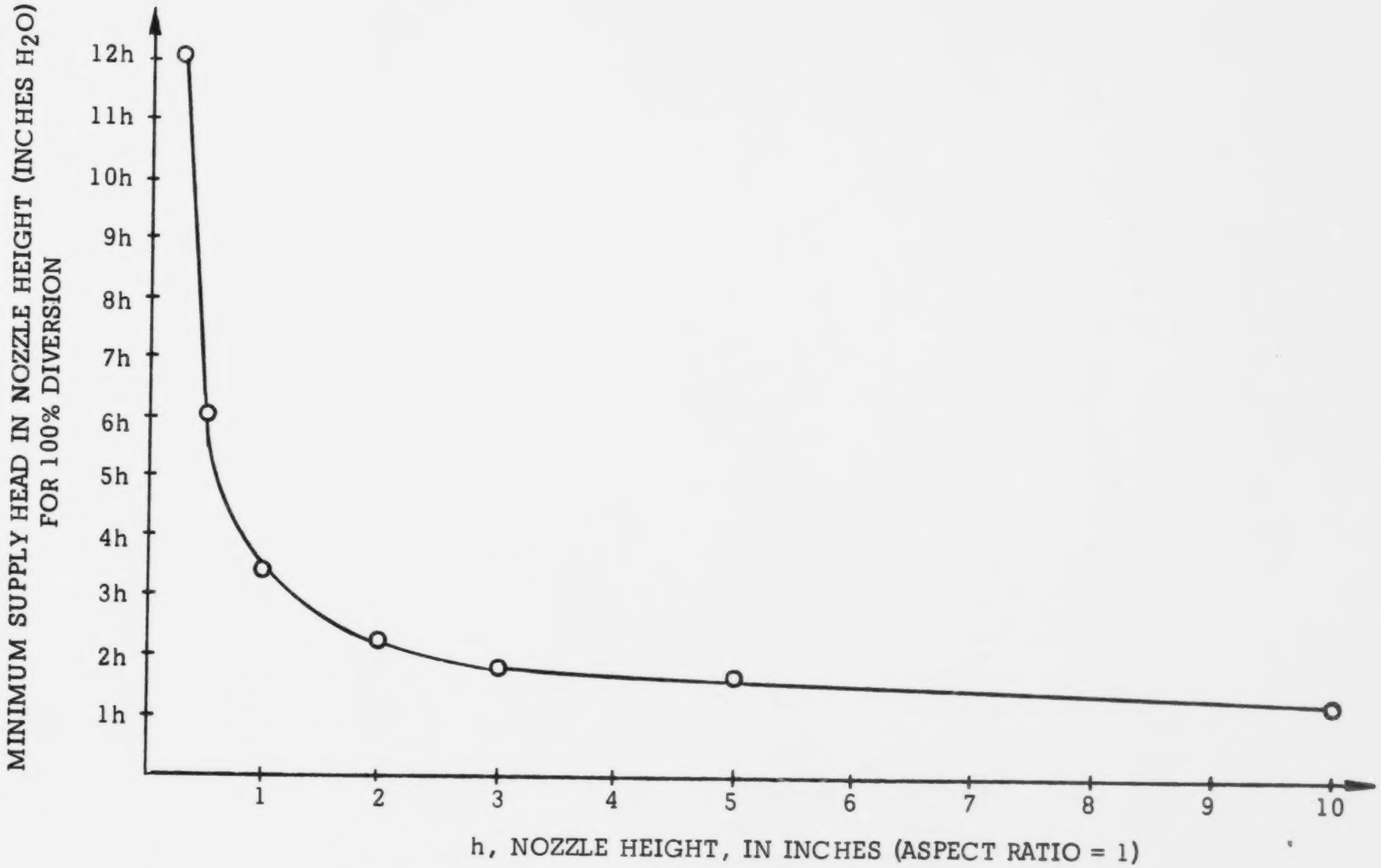


Figure 30. Minimum Head vs Nozzle Height for 100% Diversion of Fluidic Irrigation Diverters

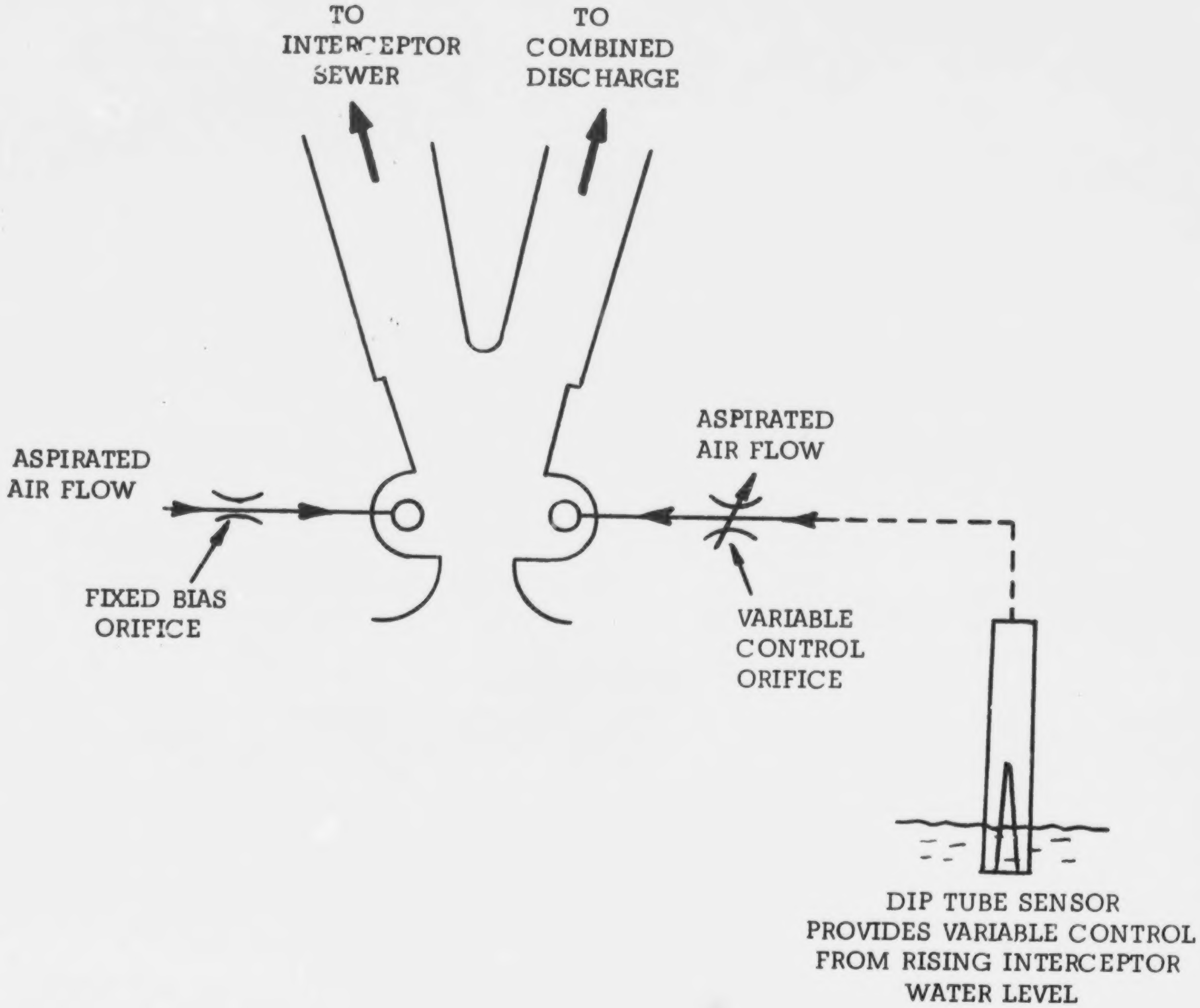

TO INTERCEPTOR SEWER
TO COMBINED DISCHARGE
ASPIRATED AIR FLOW
ASPIRATED AIR FLOW
FIXED BIAS ORIFICE
VARIABLE CONTROL ORIFICE
DIP TUBE SENSOR PROVIDES VARIABLE CONTROL FROM RISING INTERCEPTOR WATER LEVEL

Figure 31. Bias Orifice Test Circuit

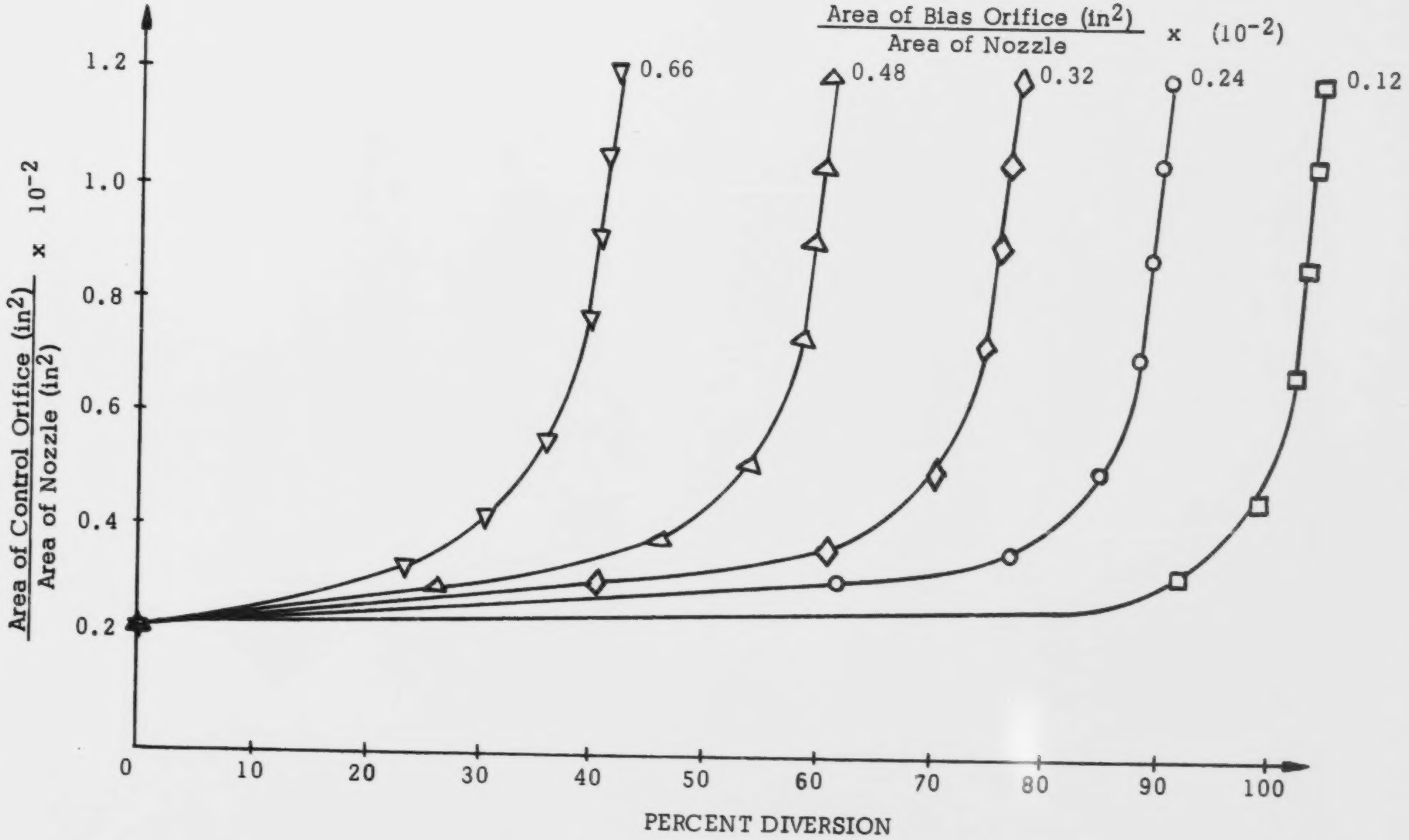


Figure 32. Sensor Control Orifice Area vs Diversion for Fluidic Sewer Regulators

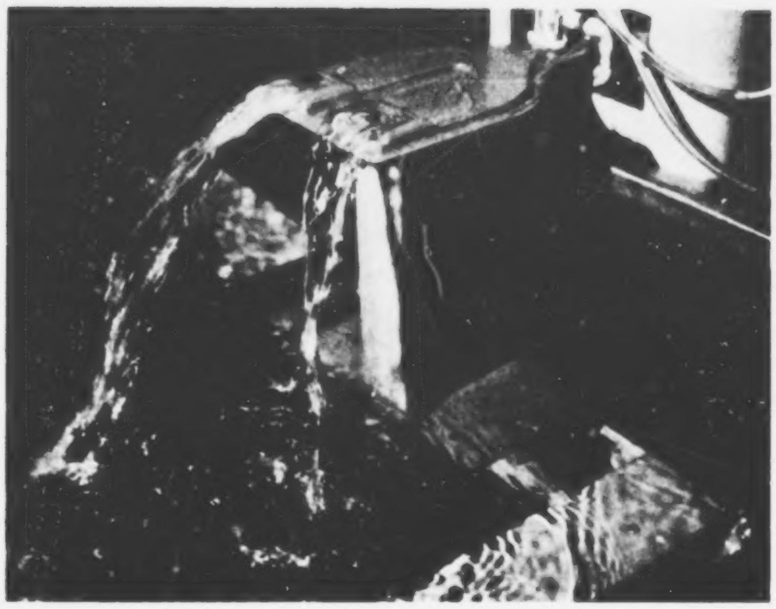


Figure 33. Irrigation Diverter Exhibiting Analog Control

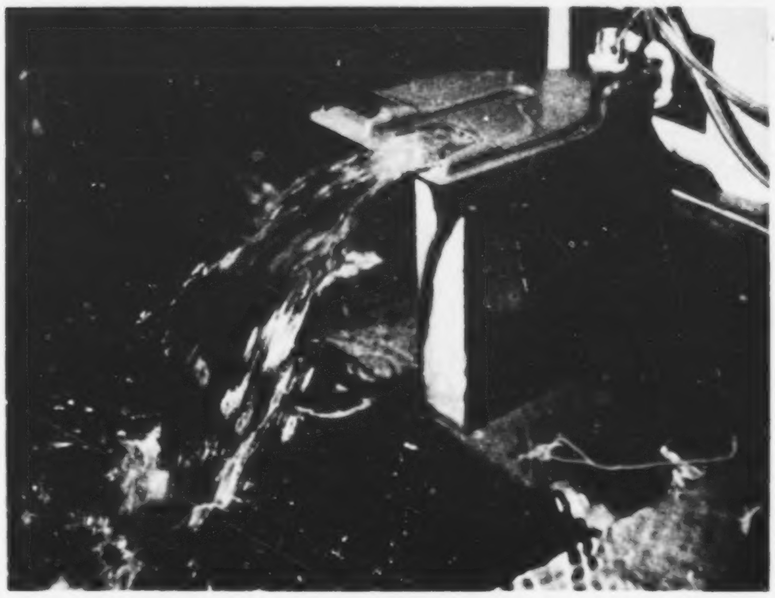


Figure 34. Irrigation Diverter in State of 100% Diversion

As pointed out above, bias orifice tests showed that a region of analog control existed in the performance of the digital irrigation diverter tested. In order to gain some insight into the results of changes on geometry to analog performance two basic modifications were tried on the 1/2" x 1/2" nozzle diverter. The normal 12.5% setback of the sidewalls was changed to zero and 21%, and diversion performance data taken, see Figure 35. Decreasing setback to zero reduced the diversion considerably, whereas increasing setback to 21% had little effect. The distance of the splitter downstream was changed by one nozzle width with little effect in performance, see Figure 36. Because of poor access to the internal geometry of the small size regulator, modifications were limited. Since no improvement in analog performance was observed as a result of these modifications, additional changes were planned for the larger size scale model tests.

As a result of test data taken from the standard 1/2" x 1/2" nozzle irrigation diverter and comparisons made with the 8" x 8" irrigation diverter, several significant and reliable scaling parameters were determined as follows:

1. Flow through regulators vs supply head for any size regulator nozzles, Figure 10.

2. Orifice coefficient vs supply head for any size regulator nozzles, Figure 11.

3. Supply head vs nozzle height required for maximum diversion performance, Figure 30.

4. Diversion vs control orifice area for fixed bias orifice areas, Figure 32.

The testing carried out in this portion of the program also provided insight into a test procedure and element design for the scale model testing. The predictive analysis made from the tests provided a good foundation for the starting of larger size regulator tests, particularly in choosing supply heads and control sizes.

Sewer Regulator Model Development

Regulator configurations similar to that shown in Figure 37 having a geometrical bias were tested for single control analog operation. In such a configuration the water stream would normally attach to the left sidewall and flow into the interceptor as long as the control sensor in the interceptor was open to permit maximum aspiration. When aspiration was reduced by interceptor flow level on the dip tube sensor, the water stream would be pulled away from the left sidewall in proportion to the

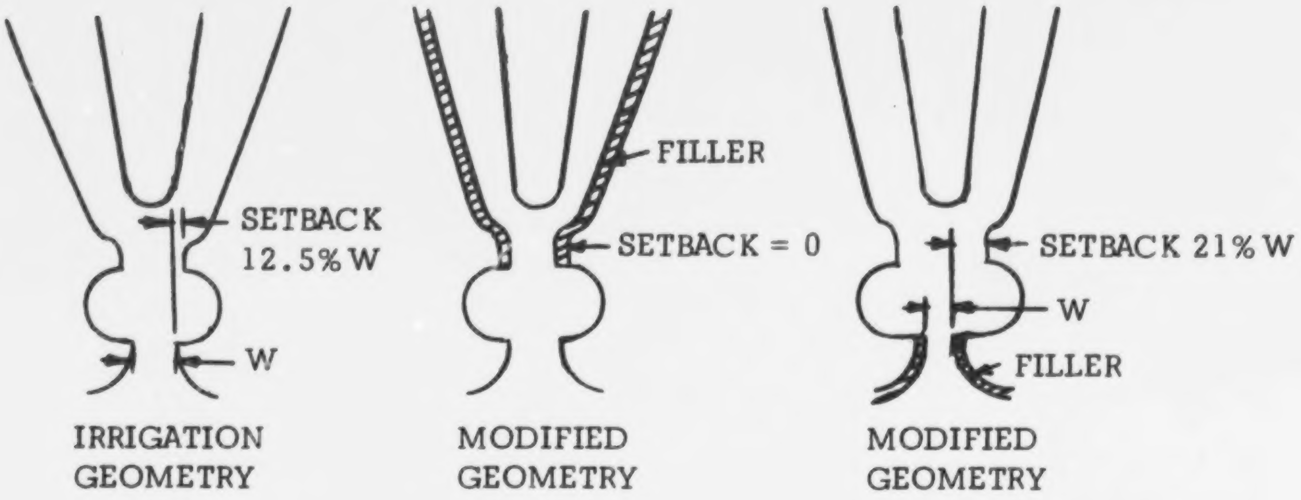

SETBACK
12.5% W
W
IRRIGATION GEOMETRY
FILLER
SETBACK = 0
MODIFIED GEOMETRY
SETBACK 21% W
W
FILLER
MODIFIED GEOMETRY

Figure 35. Changes in Setback Geometry

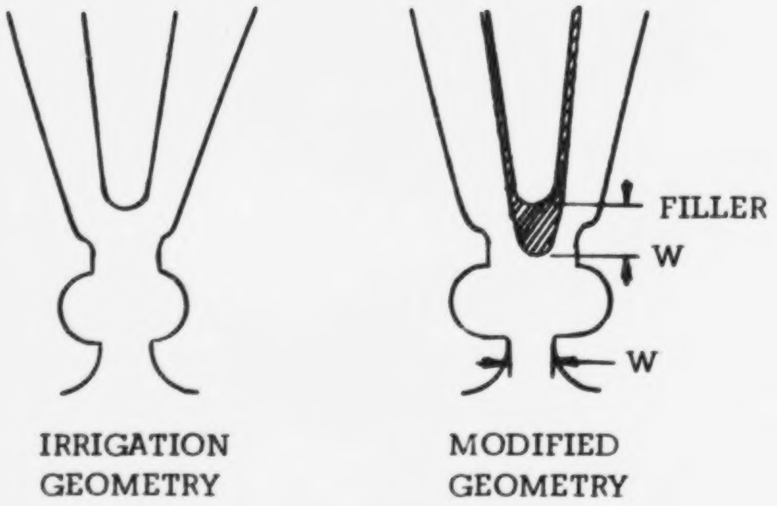

IRRIGATION GEOMETRY
FILLER
W
W
MODIFIED GEOMETRY

Figure 36. Changes in Splitter Geometry

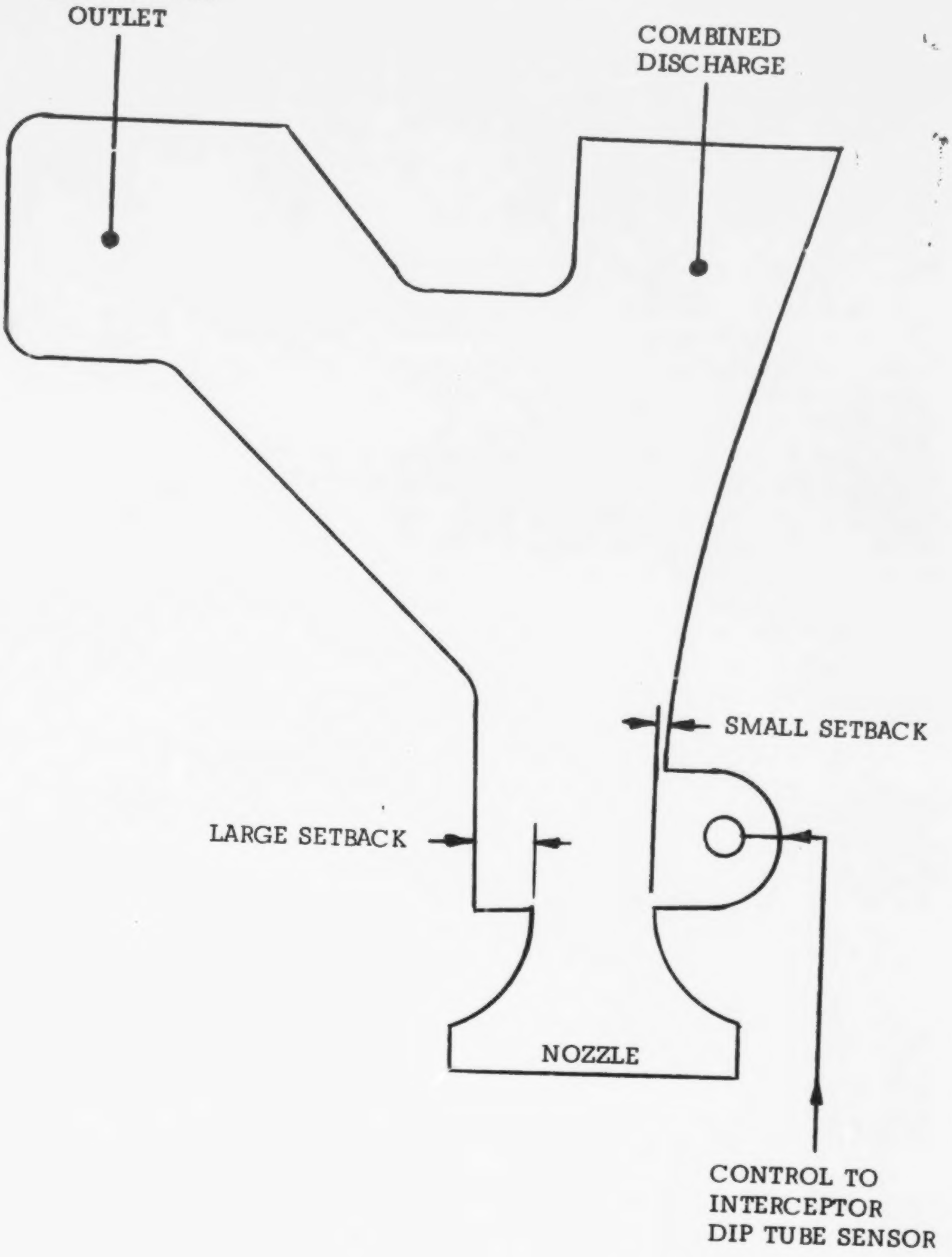

INTERCEPTOR OUTLET
COMBINED DISCHARGE
SMALL SETBACK
LARGE SETBACK
NOZZLE
CONTROL TO INTERCEPTOR DIP TUBE SENSOR

Figure 37. Geometric Bias Test Configuration

aspirated flow change until the jet was attached to the right sidewall and all flow was directed to the combined discharge. Tests of this geometry showed that geometrically biased elements could be made to perform as described above; however, the geometry was extremely critical. The maximum diversion performance was generally less than 60% into the combined discharge. Also, in the course of testing biased configurations, it was not possible to duplicate any of the acceptable designs. As a result of this critical geometry problem this approach was dropped as impractical and no further investigations were made.

Irrigation Configuration Modifications

In an effort to develop an analog diverter controlled by air aspiration, a 2" x 3" nozzle size irrigation configuration was made to adopt to the sewer simulation test setup shown in Figures 38 and 39. The basic irrigation geometry shown in Figure 40 was tested with bias orifice control as described above. In an attempt to obtain better analog performance, tests were made with several splitter variations, including pointed, round, flat, and concave shapes; and several weir settings. Results showed no improvement in analog performance over the digital irrigation diverter. The nozzle size was then changed to 2" x 1" (aspect ratio = 2) to provide a greater range of flexible geometry variations. Variations were then made in control pocket size, setback, cutaway of sidewall, sidewall length, sidewall curvature, downstream sidewall setback, and splitter bluntness and downstream location. See Log of Sewer Regulator Tests, Appendix A, for a detailed account of these tests. As a result of the testing, a 2" x 1" element configuration and sensor were developed having linear analog aspiration control over a 0 to 90 percent diversion range. The results of the control parameters tested were as follows.

The size of the control pockets were varied from 0.875W to 3W, see Figures 40 and 41 (W = width of nozzles, see Figure 12). As the pocket size is increased above W the diversion control is reduced until at 3W there is no aspiration control.

The setback of the regulator sidewalls was varied from 1/2W to zero, see Figure 35. As the setback approached zero, control rapidly deteriorated until at zero setback there was no control. As setback increased above 1/4W total diversion decreased slightly and control became more digital.

The difference in linearity and control range of rounded vs pointed splitters was not significant; however, splitter location downstream of the nozzle did cause considerable effect on analog performance and linearity. Moving the splitter closer to the nozzle as shown in Figure 36

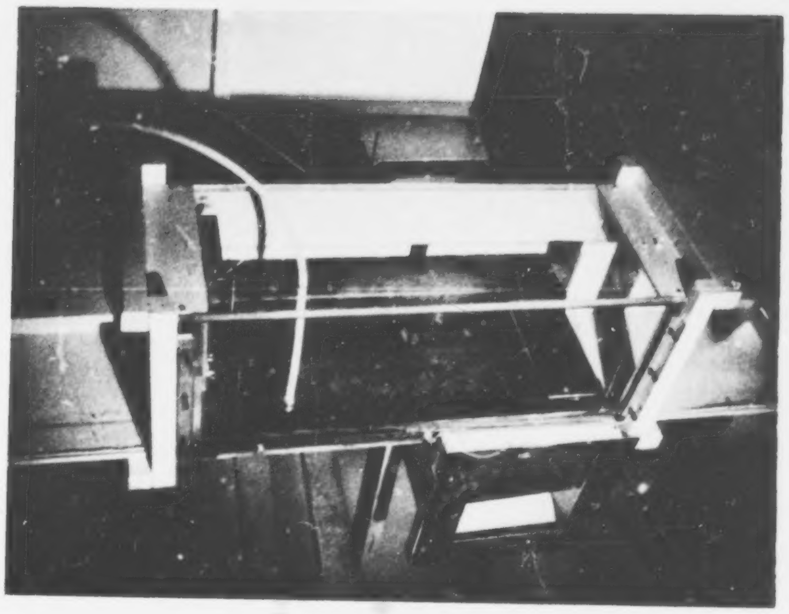


Figure 38. Model Test Configuration Showing Combined and Interceptor Sewers and Element Insert

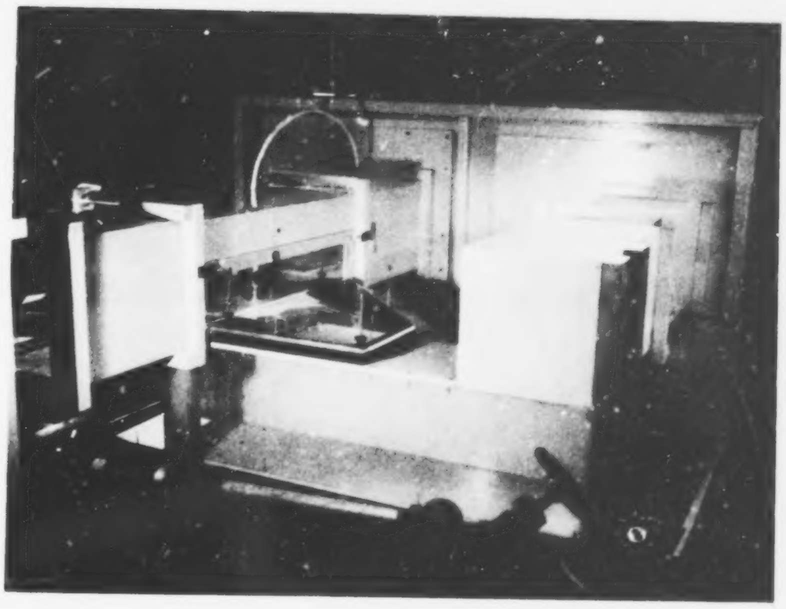


Figure 39. Model Test Configuration Showing Combined and Interceptor Sewers and Element Insert

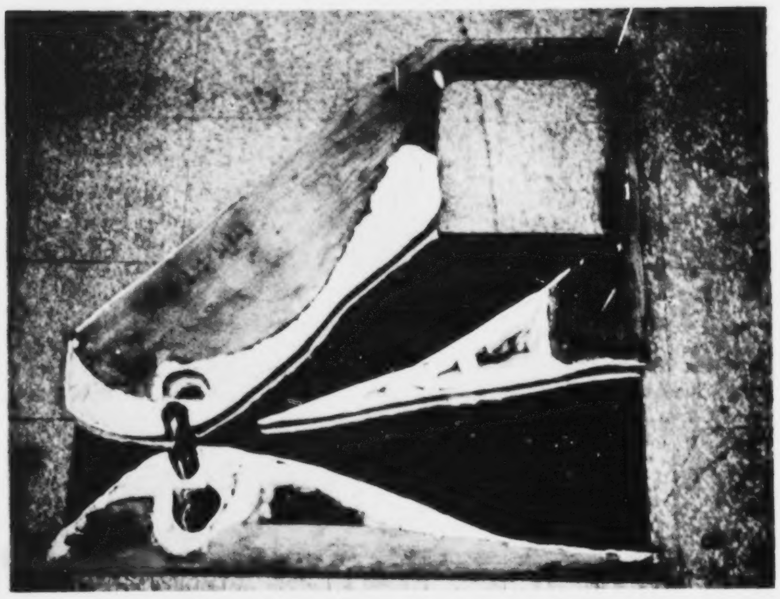


Figure 40. Basic Irrigation Test Model with 2" x 1" Nozzle

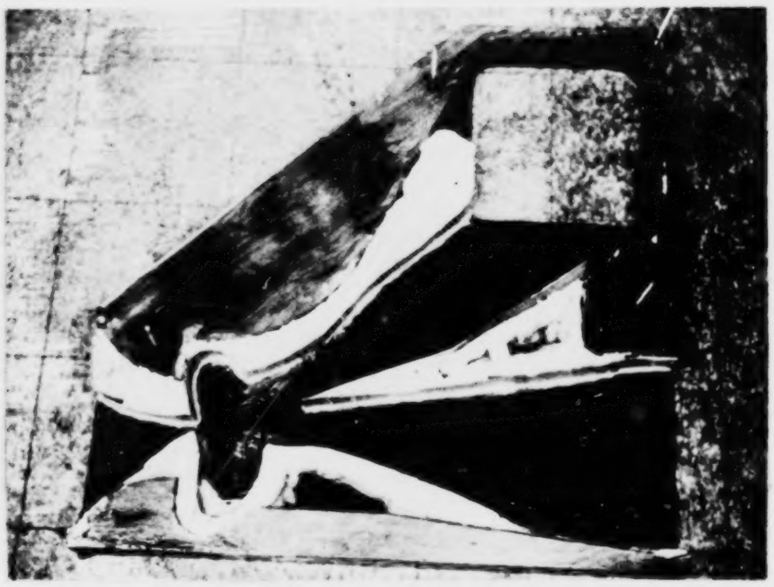


Figure 41. Large Control Pockets on Irrigation Geometry Nozzle 2" x 1"

increases the total diversion range and improves linearity. If the splitter is rounded as shown in Figure 46, performance is not degraded. A very blunt splitter as shown in Figure 37 does degrade performance.

If the sidewall is cut away at the control cavity as shown in Figure 42, the water stream cannot be diverted significantly in either a digital or analog fashion, regardless of other variations in geometry. If a short sidewall is left downstream of the controls and then cutback as shown in Figures 43 and 45 analog performance can be obtained with good total diversion characteristics. As the length of the sidewall is made longer than W, operation becomes more digital. As the length of the sidewall is made shorter than W the diversion range is shortened. Rounded sidewalls as shown in Figure 44 did not improve performance. The setback downstream of the sidewalls was also found to effect performance. A setback of 1/8W produced better total diversion than did larger setbacks. See Figures 46 and 47.

During the tests of geometrical variations on analog diversion performance several sensors were tested to obtain best analog control. A mechanical float valve was found to be best and was used for testing the other parameters discussed above. A discussion of sensor tests and designs follows.

A long necknozzle was tried, see Figure 50; however, this was found to reduce the venturi effect of the nozzle and consequently degraded diversion performance. Nozzle variations also showed that performance was not affected by minor changes in the nozzle centerline relative to the element splitter.

The best 2" x 1" nozzle configuration as shown in Figure 47 was scaled to form 2" x 4" and 4" x 4" nozzle size regulator elements to test geometry at different aspect ratios. Basic variations were made in control pockets, see Figures 48 and 49, and splitters, see Figures 51 and 52. The regulator performance varied as a result of these changes in the same manner as the 2" x 1" nozzle configuration. It was therefore assumed that an acceptable final geometry had been obtained. See Figure 12.

Performance Tests - Final Configuration

After the final geometry was obtained as a result of the extensive testing of numerous configurations as described above, the final configuration was then tested in 2" x 1", 2" x 4", and 4" x 4" nozzle regulator elements. The purpose of this testing was to obtain performance design curves which could be used to design a sewer regulator for any particular installation when given the requirements of the installation.

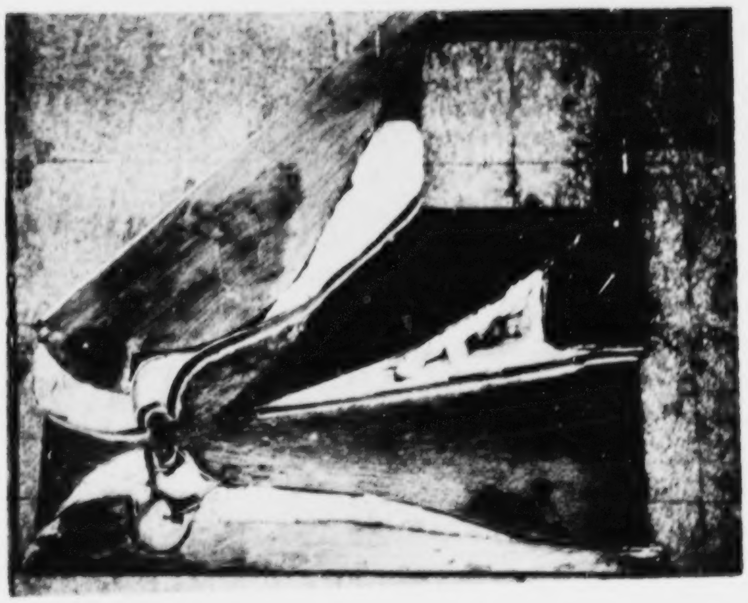


Figure 42. Cutaway Sidewalls on Irrigation Geometry Nozzle 2" x 1"

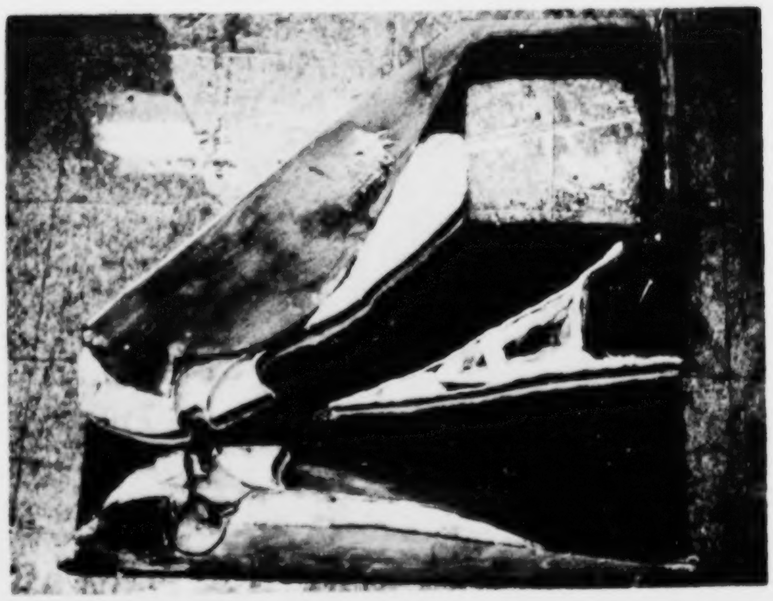


Figure 43. Short Sidewalls with Cutaway Nozzle 2" x 1"

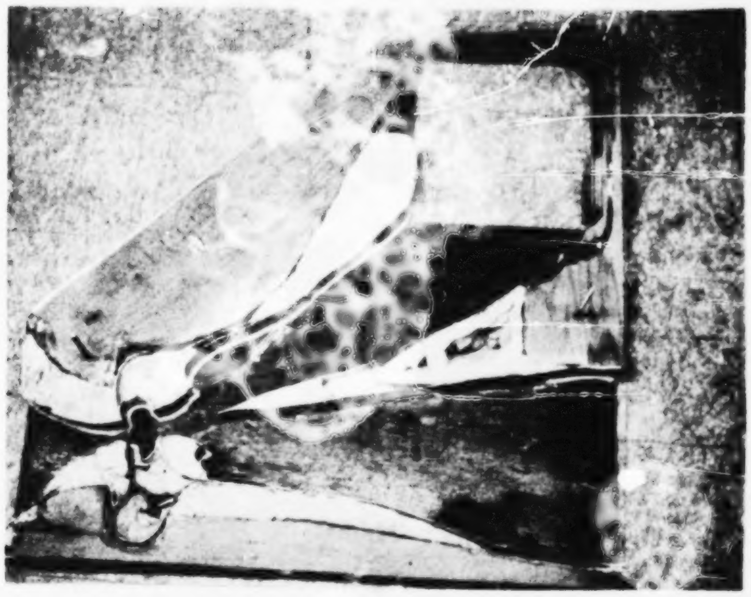


Figure 44. Rounded Sidewalls with Cutaway Nozzle 2" x 1"

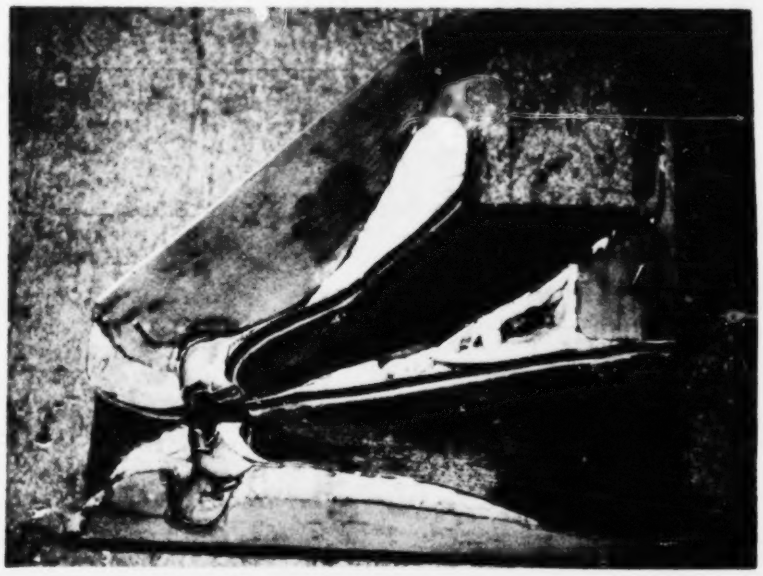


Figure 45. Short Sidewalls with Splitter Upstream Nozzle 2" x 1"

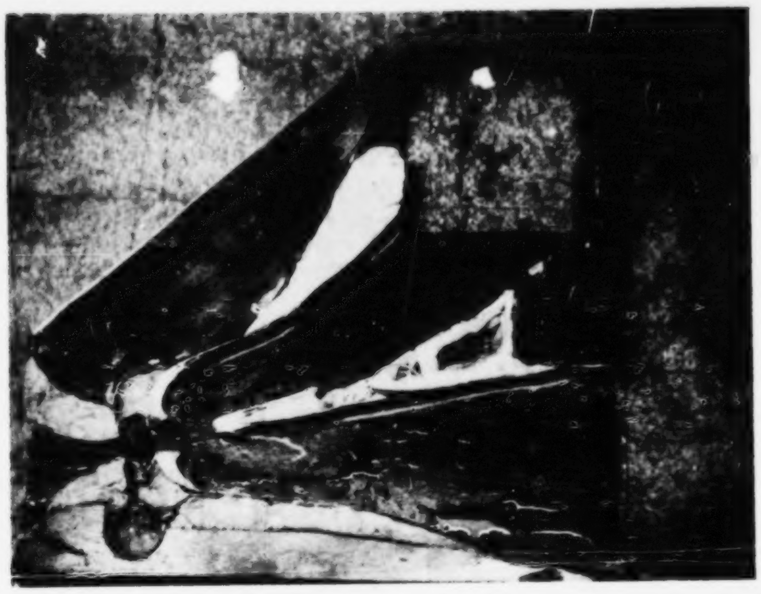


Figure 46. Short Sidewalls Rounded Splitter Nozzle 2" x 1"

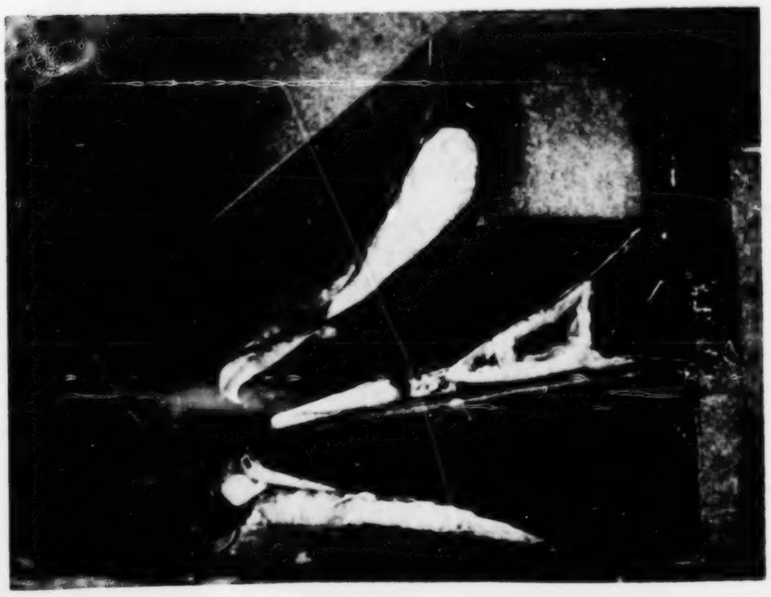


Figure 47. Short Sidewalls Rounded Splitter Less Downstream Setback Nozzle 2" x 1"

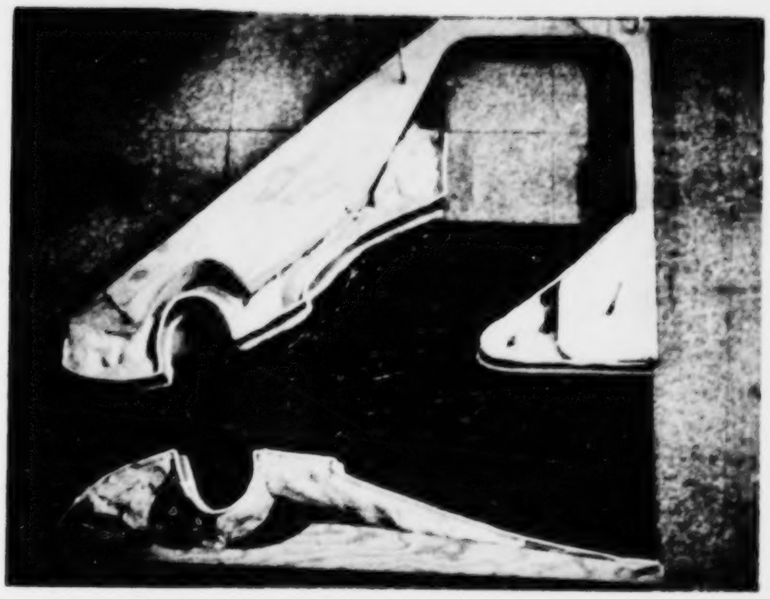


Figure 48. Analog Sewer Regulator Geometry Nozzle 2" x 4"

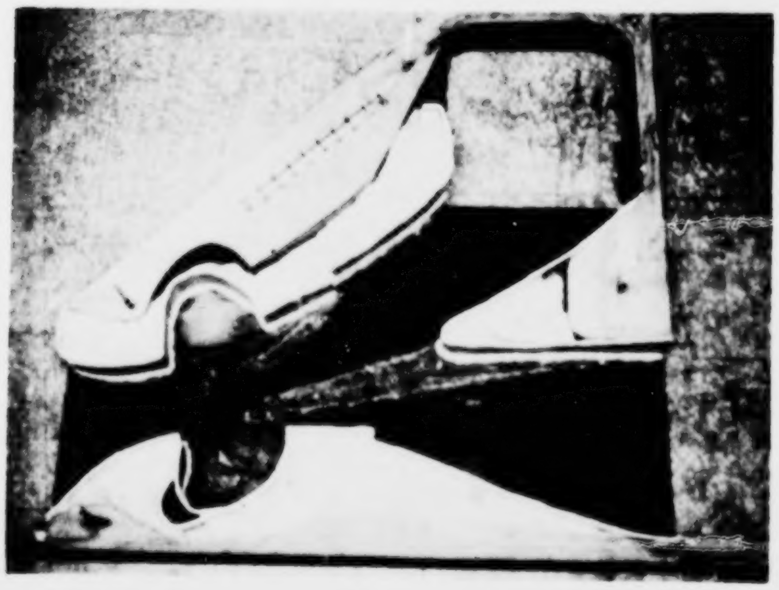


Figure 49. Analog Geometry with Larger Control Pockets and Upstream Splitter Nozzle 2" x 4"

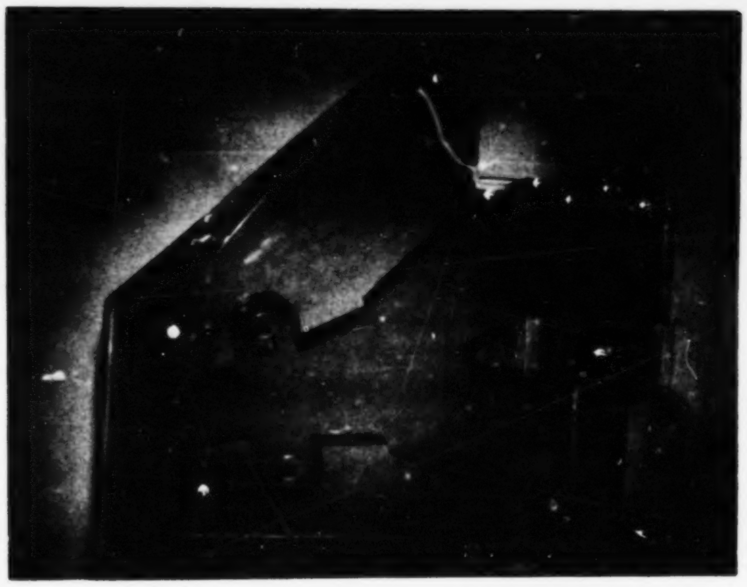


Figure 50. Analog Geometry with Long Nozzle, Pointed Splitter
Nozzle 4" x 4"

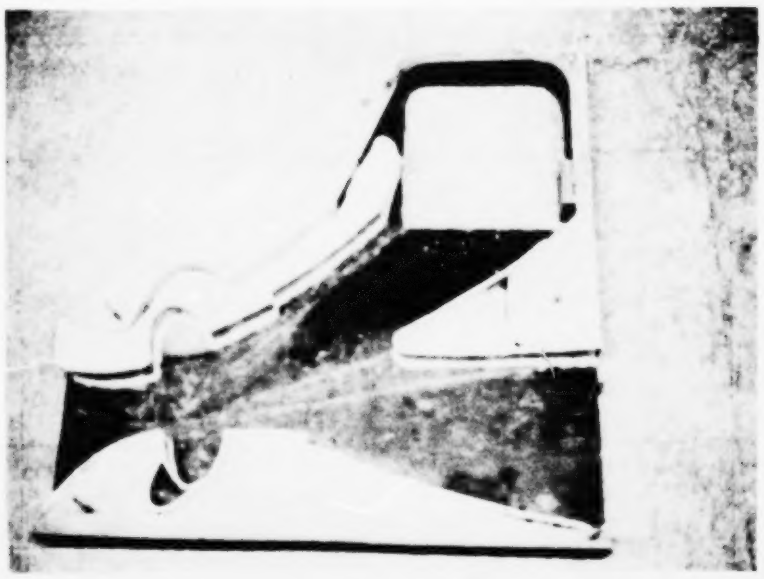


Figure 51. Final Analog Sewer Regulator Geometry
Nozzle 2" x 4"

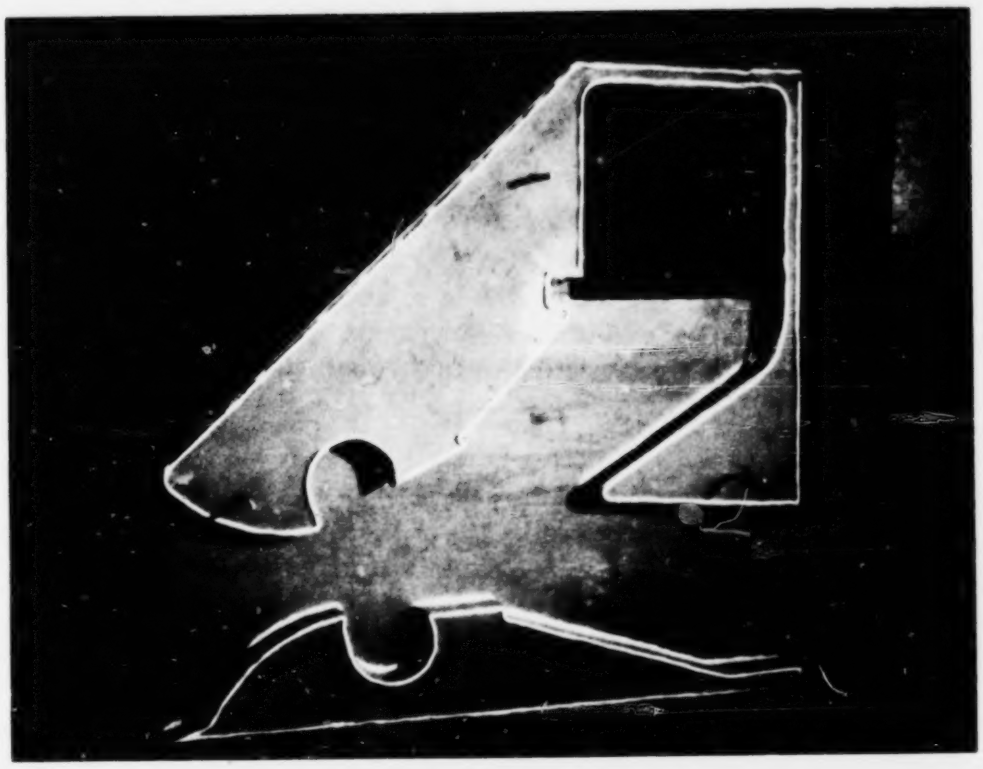


Figure 52. Final Geometry with Pointed Splitter Nozzle 2" x 4"

Diversion Performance vs Supply Head. The difference aspect ratio nozzles were tested at numerous supply heads from 6" to 18" and the maximum and minimum flows were measured to obtain the diversion range. All regulators tested were adjusted such that with the bias port completely blocked as much flow as possible was directed to the interceptor. This was accomplished by adjusting the interceptor slot opening and combined exit weir height. Design curves derived from this data are shown in Figure 53. See Appendix C for actual data. These curves show that regulators with nozzles of higher aspect ratios require less head to obtain the same diversion. It is believed that the use of these curves will result in conservative estimates of maximum diversion performance, particularly for large sewers with very low aspect ratio nozzles. This belief stems from the fact that data for the 0.25 and 0.5 aspect ratio curves were taken from tests on elements with 1 and 2 inch nozzle heights respectively, whereas the 1.0 aspect ratio curve was taken with a 4 inch nozzle element. Figure 30 shows a significant increase in head in terms of h, to achieve 100% diversion for small values of h. Note that a relatively large change in required head occurs between h = 1" and h = 4". This would indicate that the a = 0.25, and a = 0.5 curves of Figure 53 would have lain closer to the a = 1.0 curve had the tests been made on elements with h = 4" for all aspect ratios. Referring again to Figure 30, the decrease in required head from 4" up is quite small, hence the diversion performance predicted from Figure 53 for nozzle aspect ratios = 1 should be fairly accurate. With the testing of large, low aspect ratio nozzle regulators, it is expected that the accuracy of the lower aspect ratio curves of Figure 53 can be appreciably improved.

Total flow through the regulator was measured for all nozzle sizes at all heads to obtain head flow data. This was compared to the nomograph, obtained from the predictive analysis, see Figure 10 and Appendix B. Agreement was within ± 5 percent for all nozzle sizes.

Weir Settings: Interceptor Exit Design. Several configurations of the interceptor weir were investigated to obtain the most simple design with the best performance, see Figure 54. Design #1 was a conventional weir with a cut off corner that allowed low flow to pass without restriction. The discharge area in this design was distributed across the channel and provided an opening subject to fouling. Design #2 provided a larger opening by shaping the exit area into a full depth rectangular slot along the splitter wall where the high velocity stream would have a low impedance path to the interceptor. This design exhibited basic functional response problems in switching the flow to the interceptor by forming an air pocket, see Figure 54. Proper performance was obtained with this weir design by moving the opening next to the sidewall side of the element as shown by Design #3 in Figure 54.

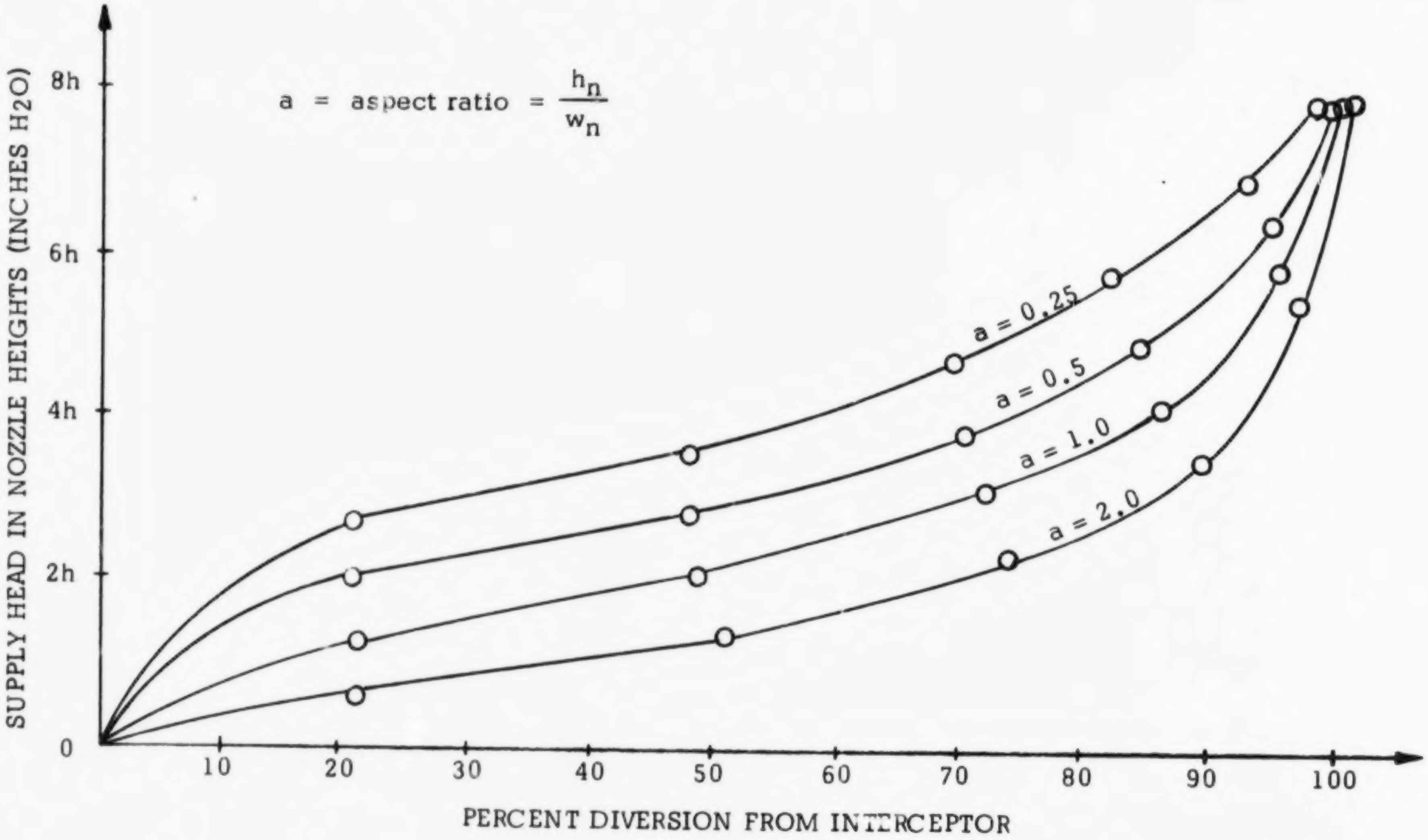


Figure 53. Maximum Diversion vs Supply Head for Fluidic Sewer Regulators

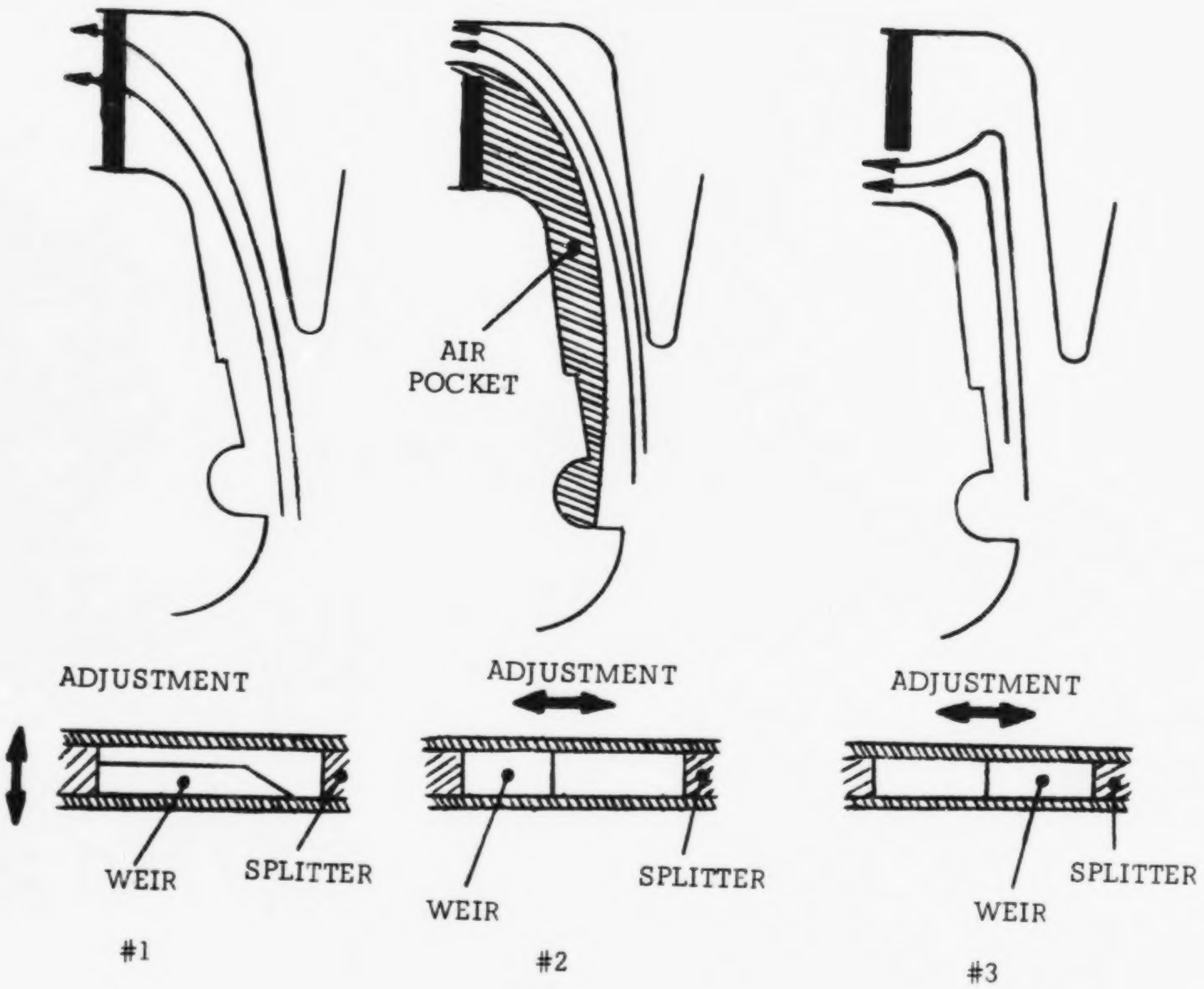

AIR
POCKET
ADJUSTMENT
WEIR
SPLITTER
#1
ADJUSTMENT
WEIR
SPLITTER
#2
ADJUSTMENT
WEIR
SPLITTER
#3

Figure 54. Interceptor Slot Configurations

In order to obtain design data concerning the proper interceptor exit area settings, the combined weir was set at various fixed levels, and maximum-minimum diversion data were taken for a complete range of interceptor exit area settings and inlet heads. These data are shown in Figures 55 and 56 in dimensionless parameters based on nozzle size and area. These characteristics proved independent of supply heads. Using Figure 56 we see that the optimum height of the combined weir is 1.4 h_n (h_n = nozzle height). Using Figure 55 we see that the optimum area of the interceptor discharge is 1.2 A_N (A_N = nozzle area). See Appendix C for actual data curves used to obtain these design curves.)

Sensor Characteristics. The predictive analysis yielded bias orifice criteria as discussed above. These data were found to hold for using single dip tube sensors and a bias control orifice to effect digital type control; however, it was found that the analog operation of the regulator could best be obtained by a sensor which would operate independently on each control and thus obtain maximum linearity. This type of control also required a sensor with very different area relationships than the bias orifice type. The development of the analog area ratios and sensor schemes are presented in the following detailed discussion.

In order to determine the sensor area relationship required for linear analog control as described above, a float valve was placed in the interceptor line as shown in Figures 57 and 58 to provide control. The schematic of the float valve test setup, Figure 59, shows how regulator control was effected by interceptor water level. When the water level is at the desired minimum point, float valve area #2 is closed by the rubber flapper and all the flow through the regulator is directed to the interceptor. When the interceptor is filled to the desired maximum level, area #1 is closed and all flow is diverted away from the interceptor to the combined discharge.

Three sensor area configurations tested in this setup are shown in Figure 60 and performance data from these sensors are shown in Figure 61. Sensor 1 consisted of small areas on the order of the bias orifice areas recommended by the predictive analysis. Performance with this size area was purely digital; that is, the interceptor water level had to raise to its maximum height to close off the sensor area #1 before any change in diversion occurred. At this point complete switching of the stream occurred with no analog control. Sensor #2 incorporated areas five (5) times as large as the areas in sensor #1. Performance with sensor #2 was still digital; however, a range of analog control was observed, as shown in Figure 61. As a result of numerous tests and observations with sensor #2, it was determined that maximum sensor area is needed when the areas are equal and the regulator is

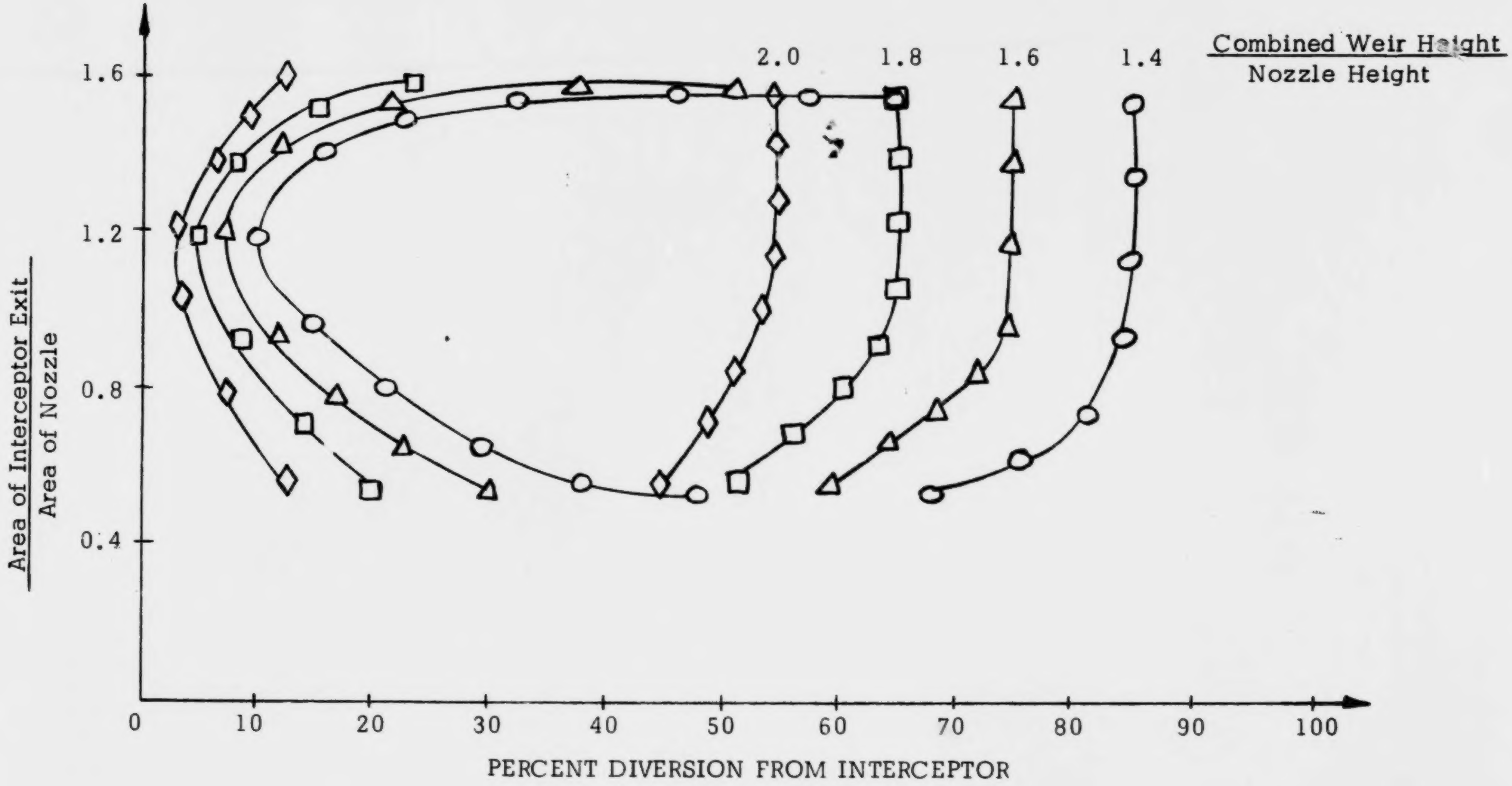


Figure 55. Minimum-Maximum Diversion From Interceptor vs Combined and Interceptor Weir Settings for Fluidic Sewer Regulators

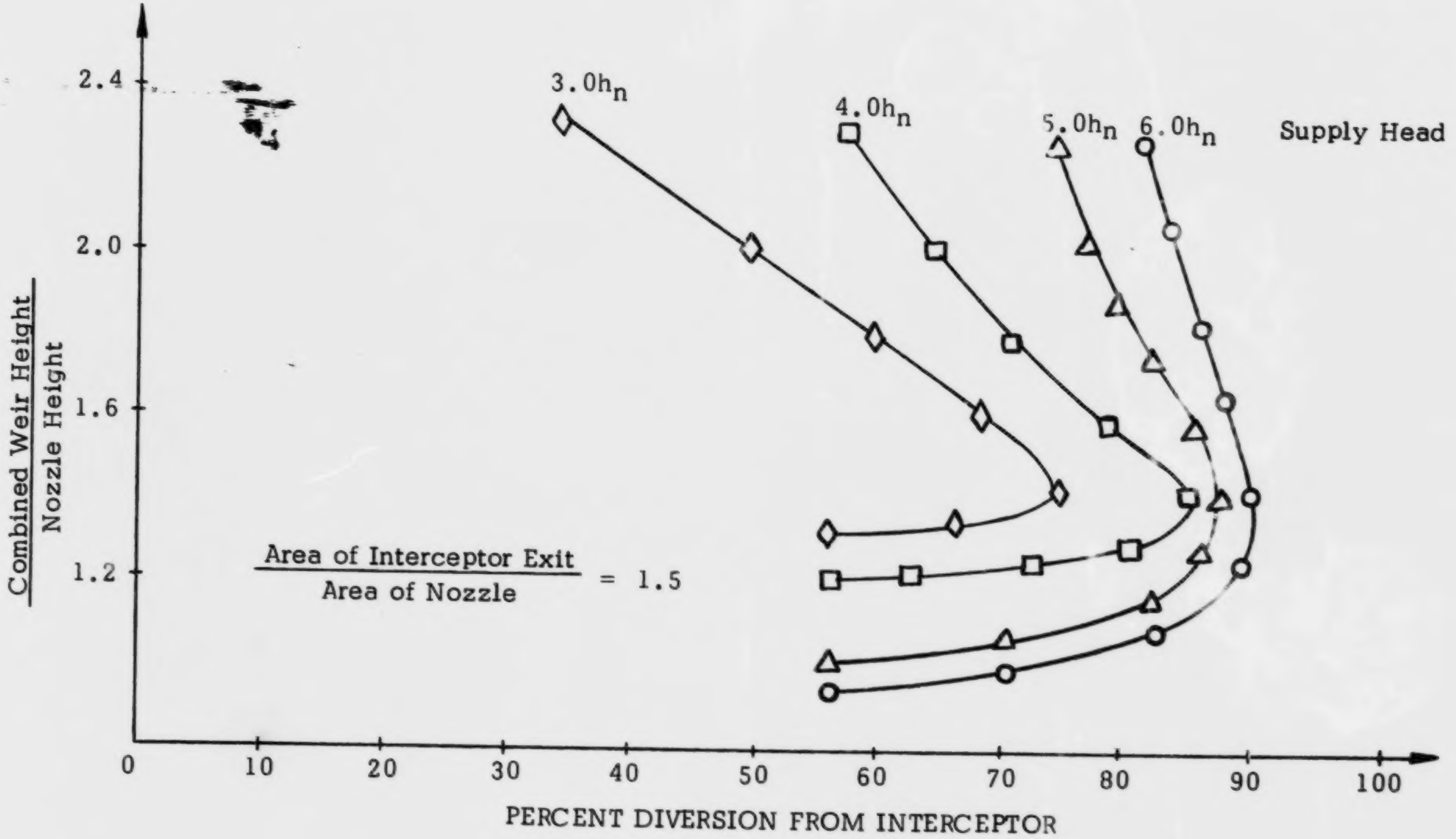


Figure 56. Maximum Diversion vs Combined Weir Height

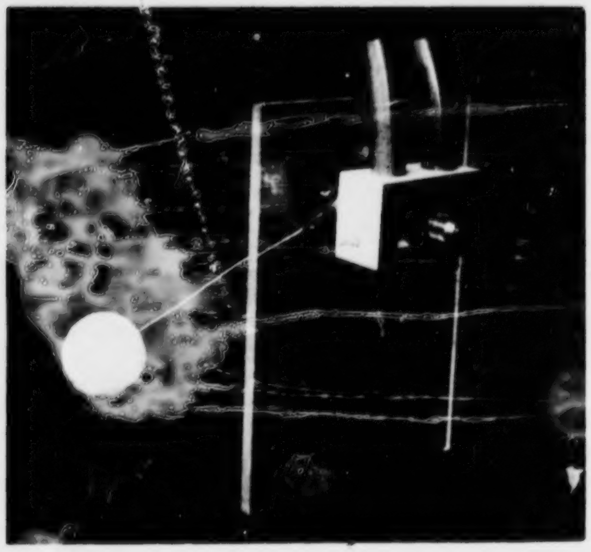


Figure 57. Float Valve Mechanical Sensor

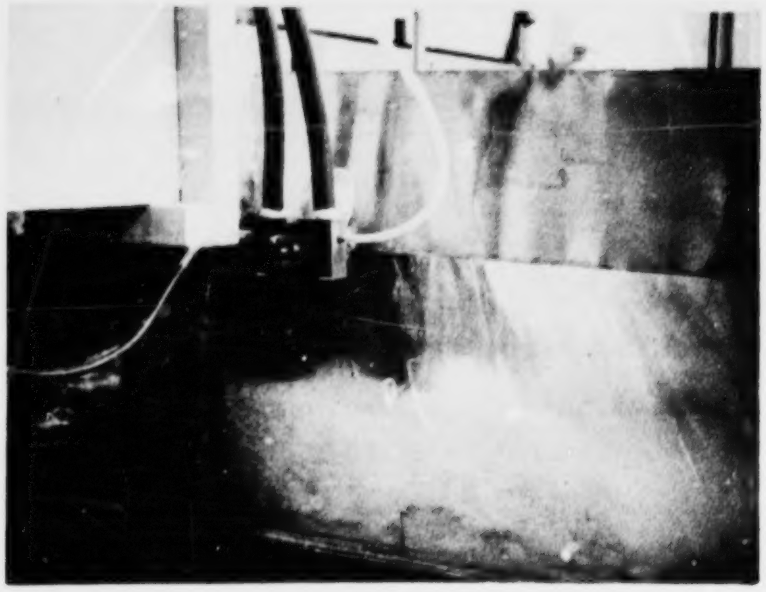


Figure 58. Float Valve Test Installation

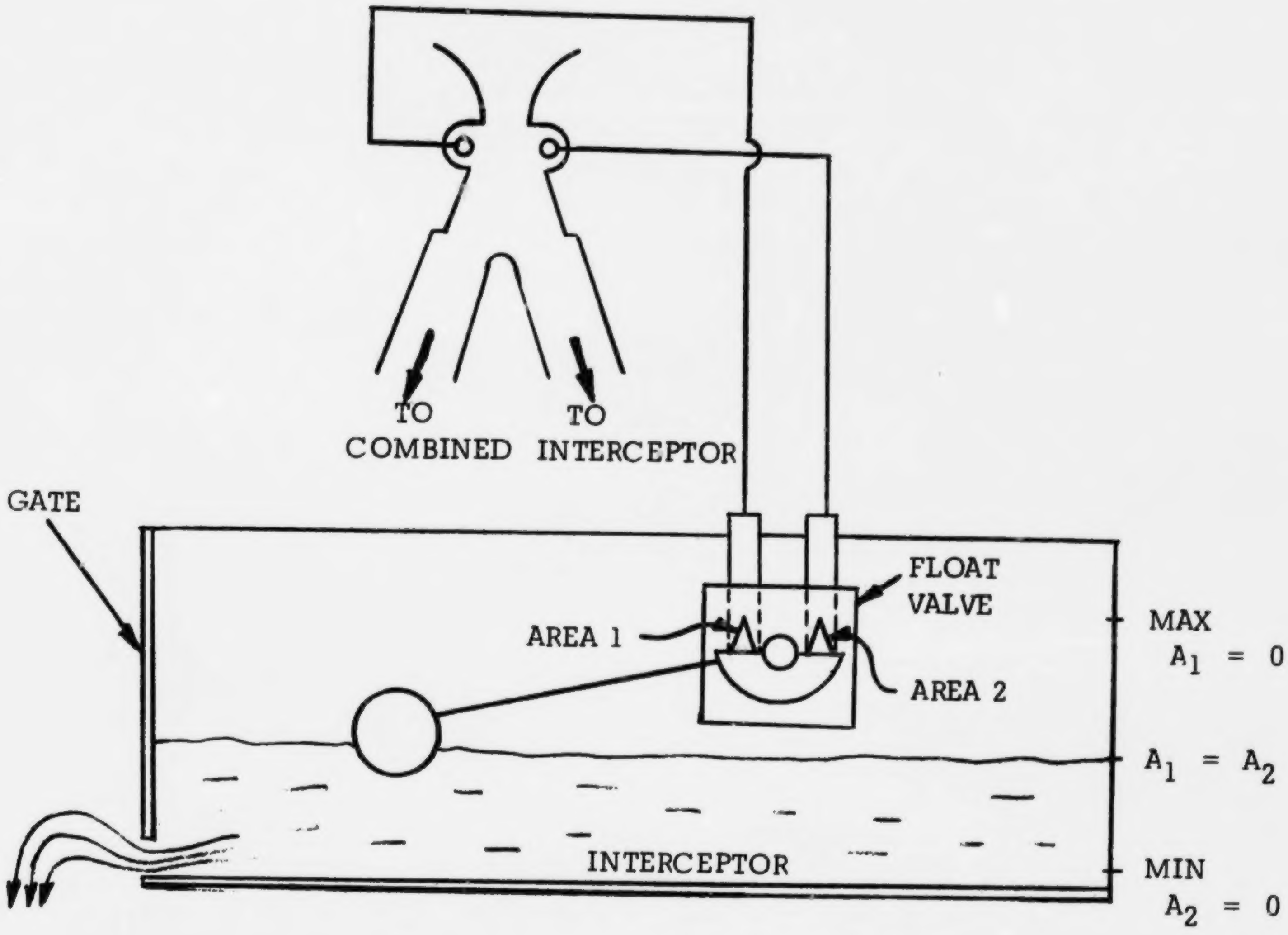
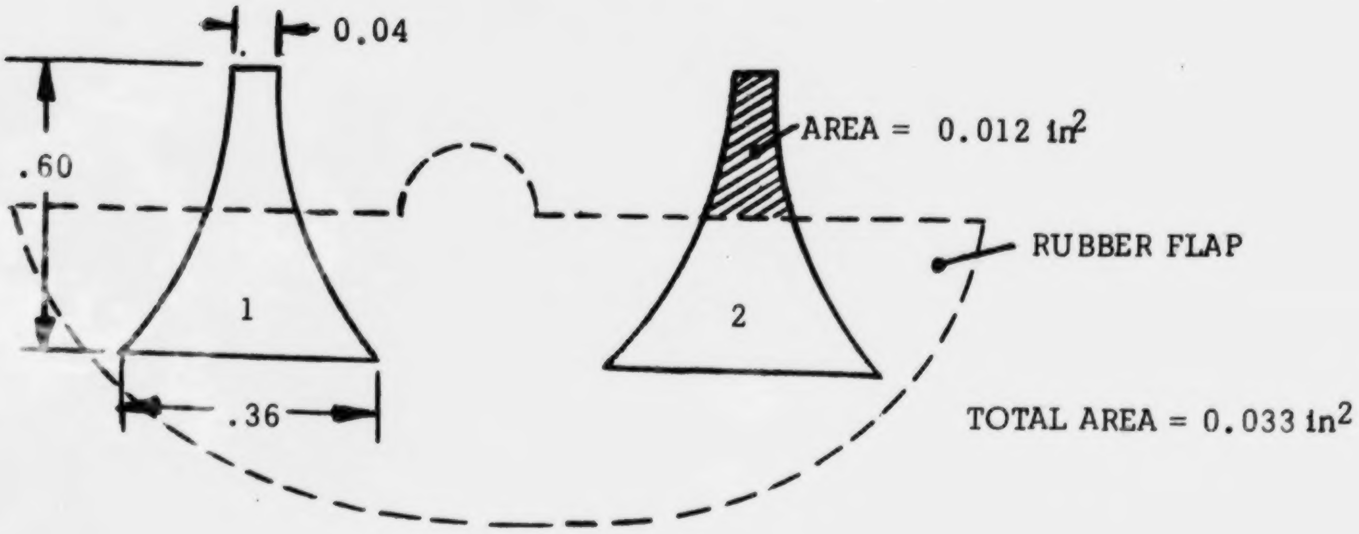
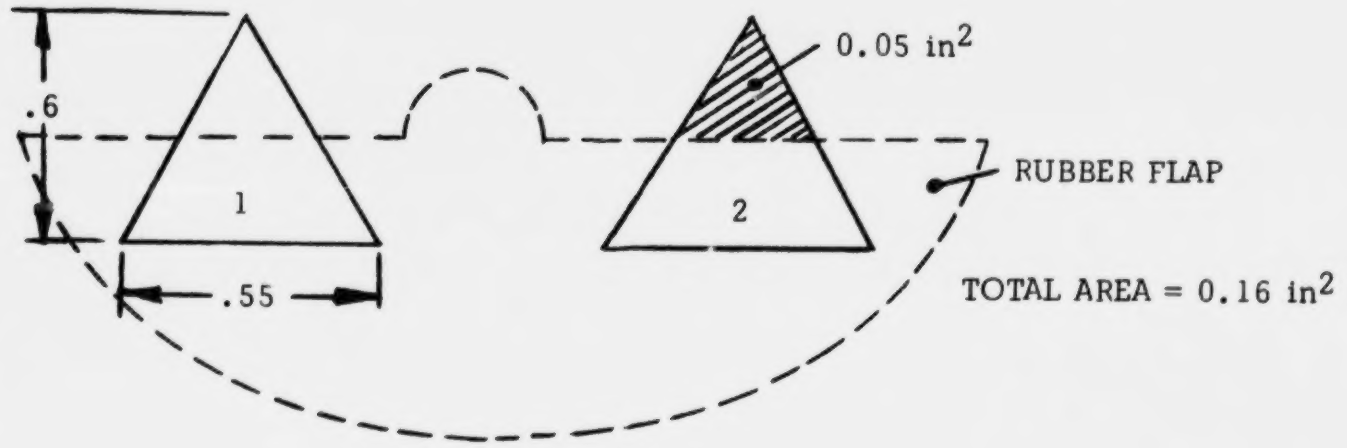

TO
COMBINED
TO
INTERCEPTOR
GATE
FLOAT
VALVE
AREA 1
AREA 2
MAX
$A_1 = 0$
$A_1 = A_2$
INTERCEPTOR
MIN
$A_2 = 0$

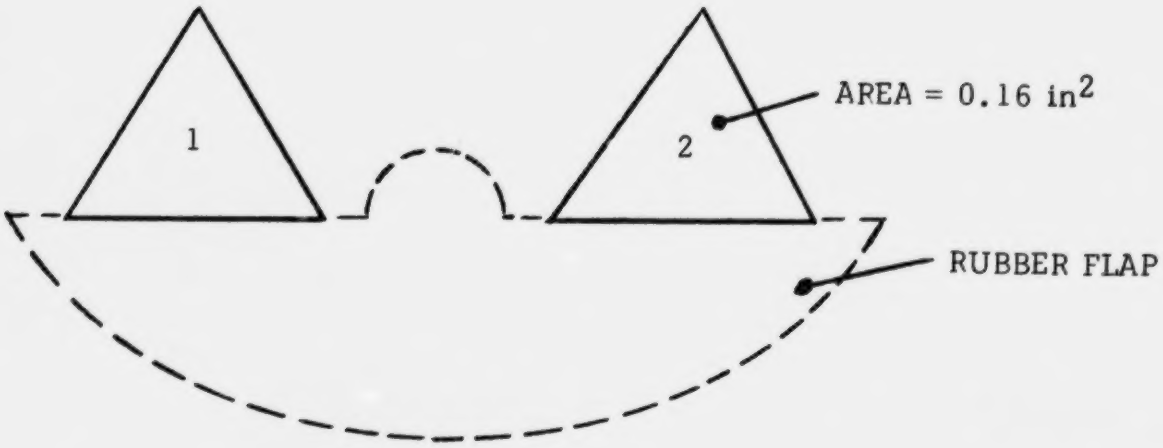
Figure 59. Float Valve Sensor Test Setup


0.04
.60
AREA = 0.012 in²
RUBBER FLAP
1
2
.36
TOTAL AREA = 0.033 in²

SENSOR 1


.6
0.05 in²
RUBBER FLAP
1
2
.55
TOTAL AREA = 0.16 in²

SENSOR 2


AREA = 0.16 in²
1
2
RUBBER FLAP

SENSOR 2M

Figure 60. Float Valve Sensor Areas

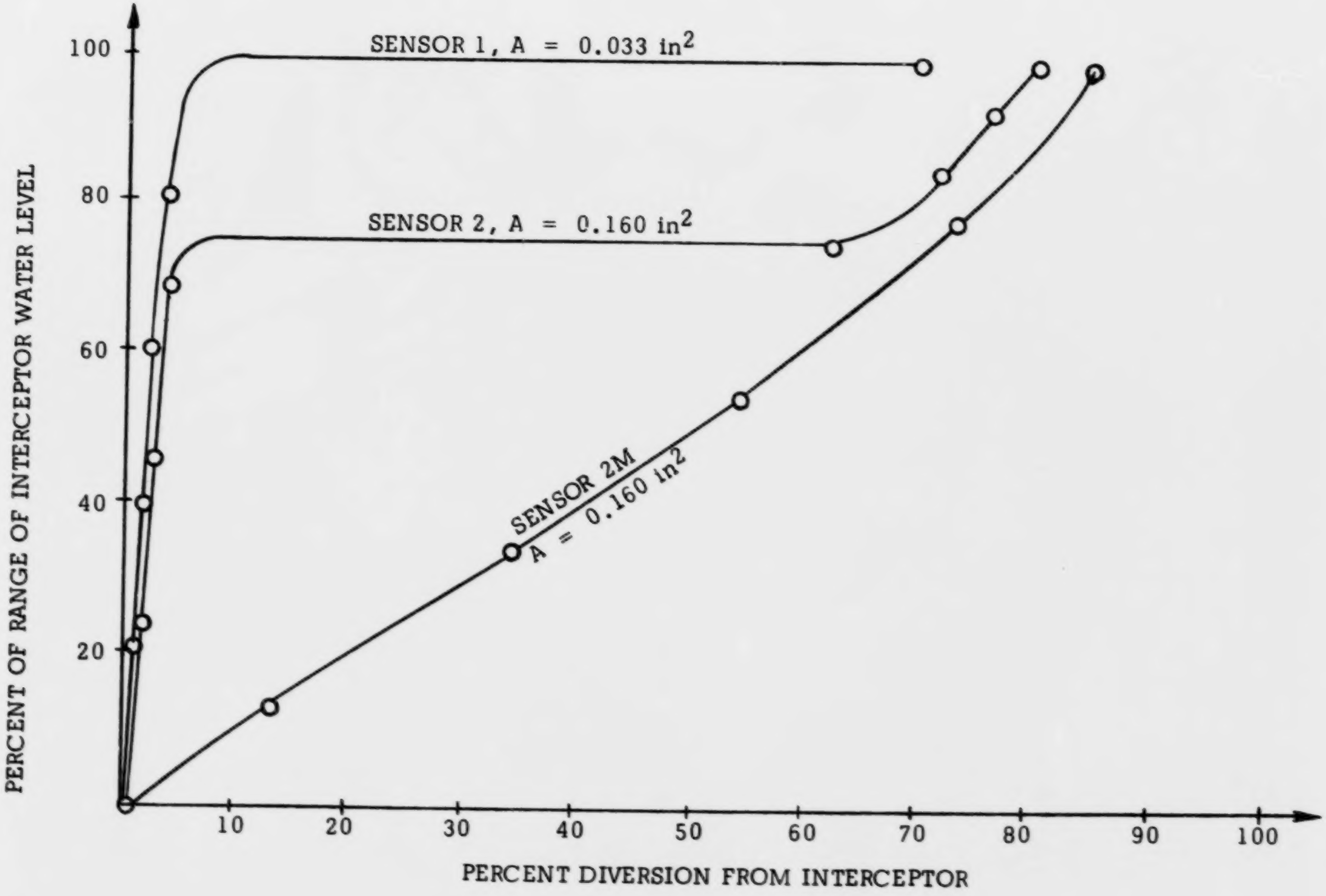


Figure 61. Diversion vs Interceptor Water Level for Fluidic Sewer Regulator 2" x 4" Nozzle

dividing the flow evenly between the interceptor and combined sewers. By gradually opening up the areas at the 50-50 operating diversion point the optimum area designated as sewer #2M was established and performance data recorded, see Figures 60 and 61.

Percent diversion vs change in sensor area was then taken for the 2" x 4" and 4" x 4" nozzle regulators, see Figures 62 and 63. Area change was recorded as a ratio of sensor area change to regulator nozzle area, as referenced from the condition where the interceptor control area is fully closed and all flow is diverted to the interceptor. The ratio corresponding to maximum diversion is then twice the area of the sensor opening used for each control. Test results from both 2" x 4" and 4" x 4" nozzle regulators yielded the same ratio of 40 (10^{-3}) as the proper ratio for linear analog control.

It follows, then, that the optimum control orifice area for analog operation is 20 (10^{-3}) A_N, (A_N = nozzle area). Digital operation is obtained by using orifice areas equal to one quarter of the analog area. Tests at numerous supply heads showed diversion performance vs area change or interceptor level change was linear, over a complete range of heads, as shown in Figures 64 and 65. (See Appendix C for actual data curves.)

No-Moving-Part Sensors

Principles of Operation. In the course of this program a new design for a no-moving-part sensor was investigated which could provide linear analog control without the need for a mechanical float valve. A schematic of the arrangement is shown in Figure 66. The system uses a control dip tube in the interceptor sewer which is connected to the combined control of the regulator and a sealed bottle. A second dip tube is connected to the interceptor control and placed in a second bottle which is vented and has a common fluid connection at its base with the sealed bottle. The two bottles and connection operate in the manner of a U-tube manometer. As the interceptor dip tube sensor is covered by rising water level, aspiration through the combined control is reduced causing an increase in vacuum. This increase in vacuum acts on the sealed bottle to raise its fluid level. Since the two bottles have a common connection and the dip tube bottle is vented, a change in fluid level between the two bottles results. The change in fluid level of the bottles produces a change in the exposed area of the vented bottle dip tube, which in turn controls aspiration to the interceptor control. Therefore, an interceptor level increase will increase the aspiration to the interceptor control by increasing the opening of the dip tube slot through the bottle and decrease the aspiration to the combined control directly. The jet stream will be switched in a push-pull manner.

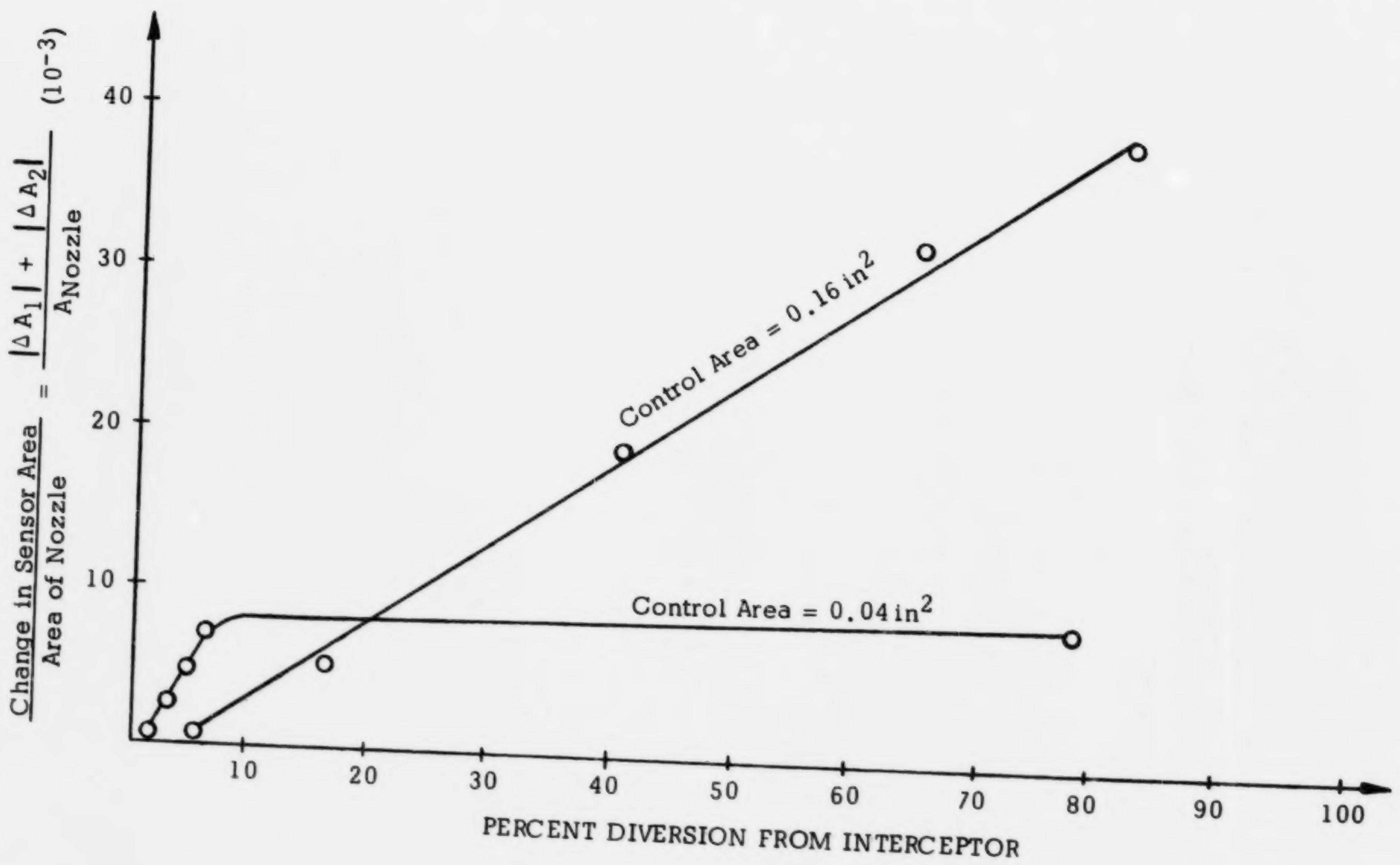


Figure 62. Diversion vs Sensor Area Change 2" x 4" Nozzle Supply Head = 13.0"

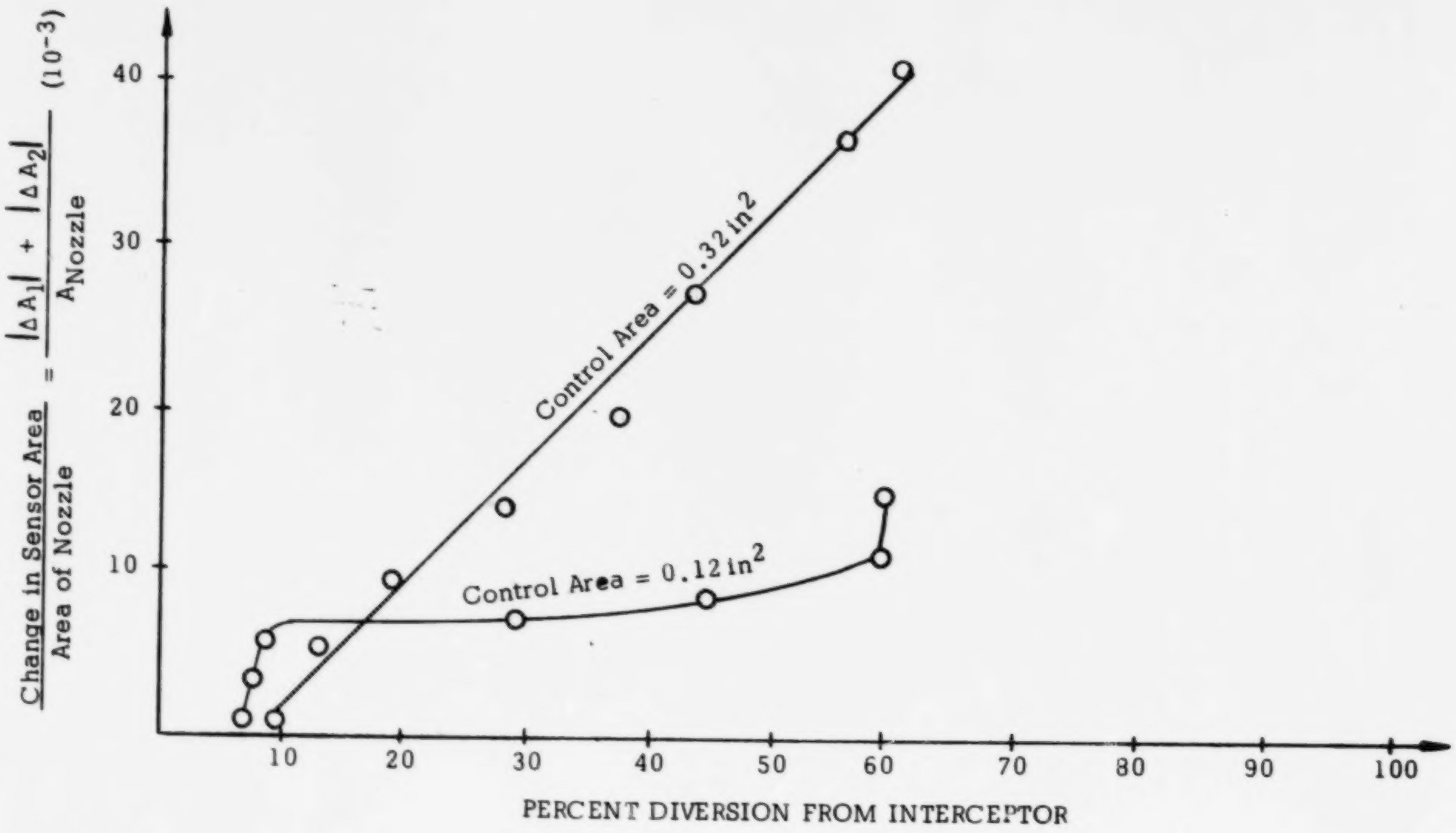


Figure 63. Diversion vs Sensor Area Change 4" x 4" Nozzle Supply Head = 13.0"

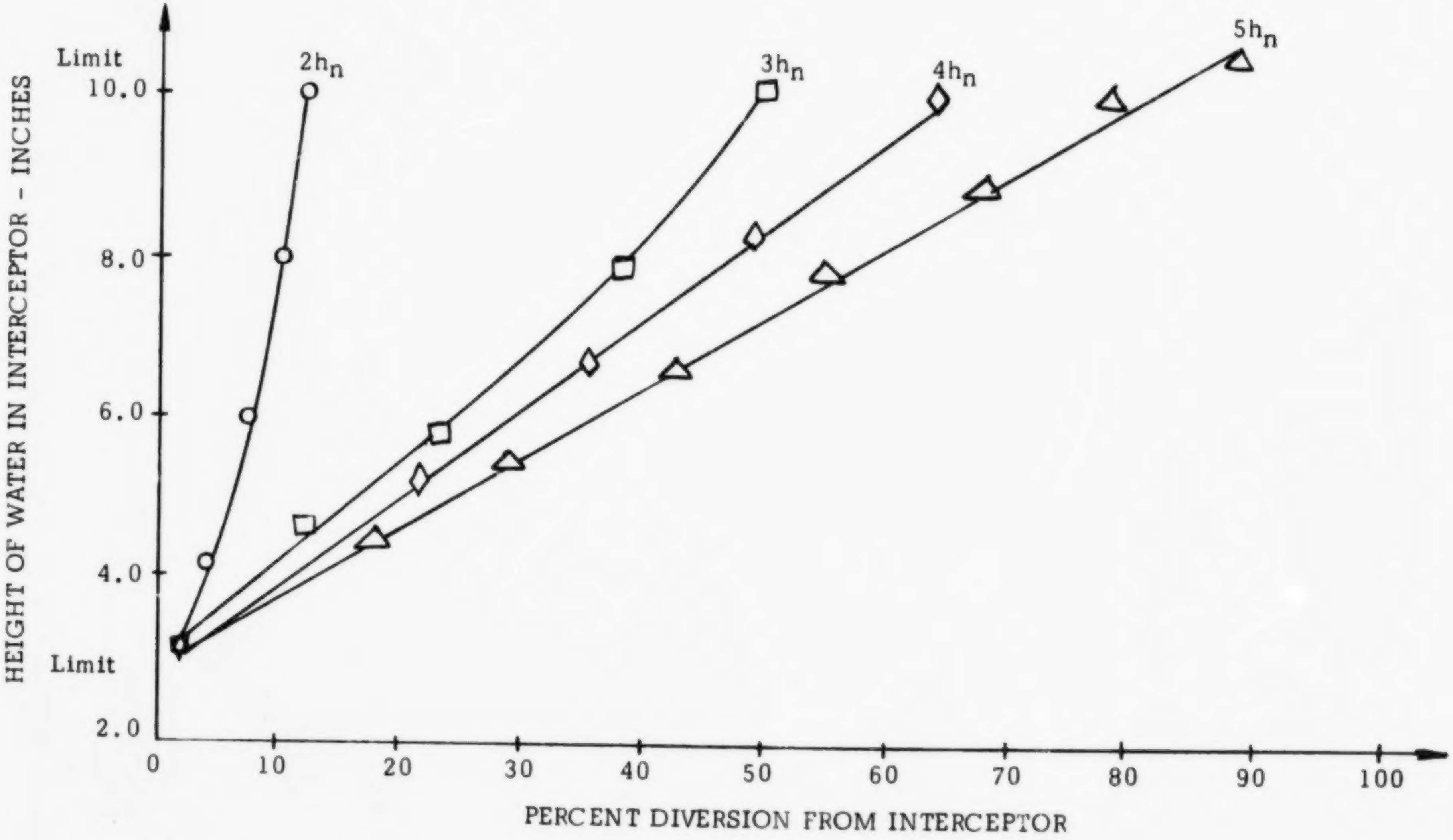


Figure 64. Diversion vs Interceptor Level for Fluidic Sewer Regulators
Aspect Ratio = 0.5 Nozzle 2" x 4"

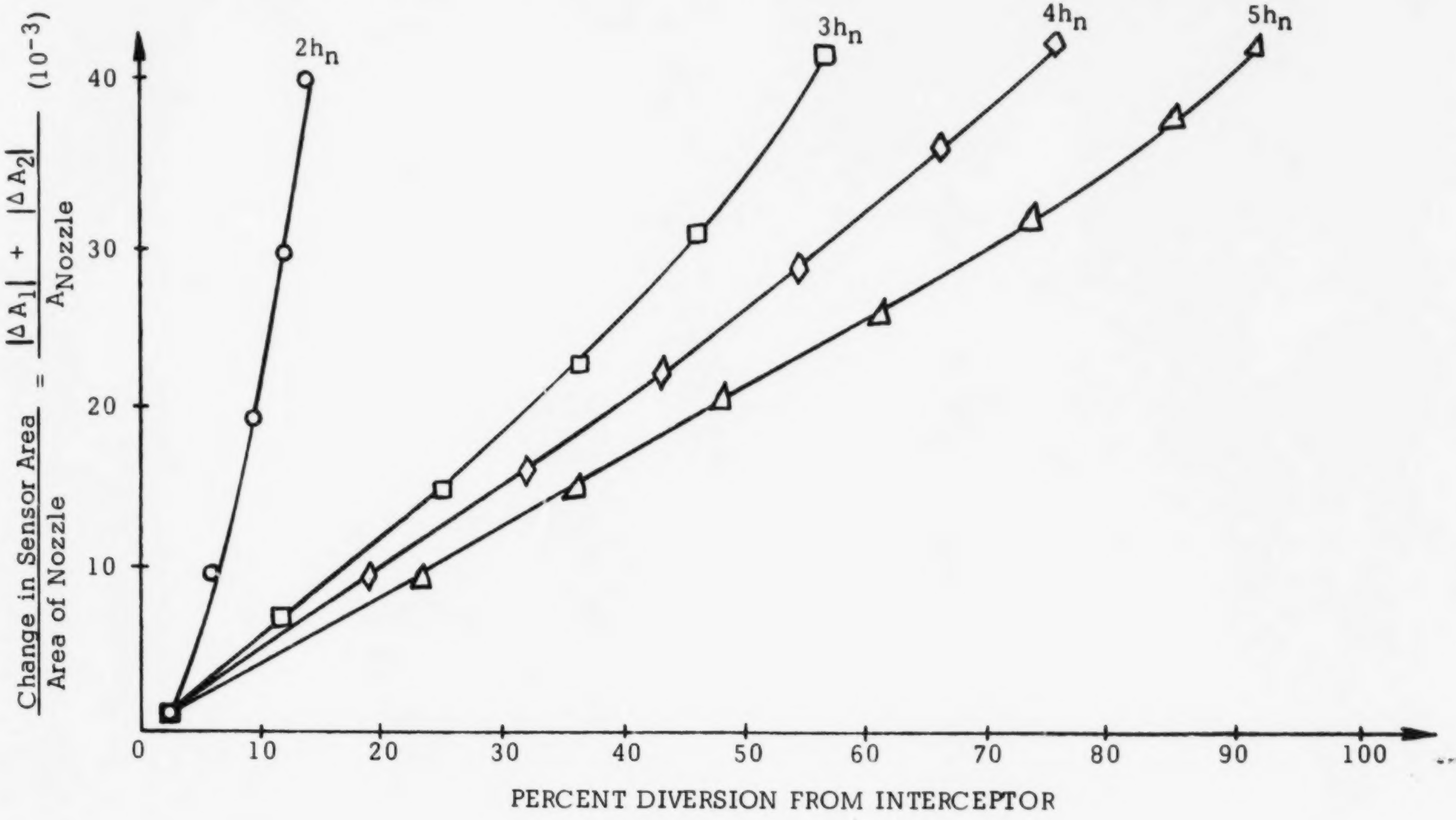


Figure 65. Diversion vs Sensor Area for Fluidic Sewer Regulators
Aspect Ratio = 0.5 Nozzle 2" x 4"

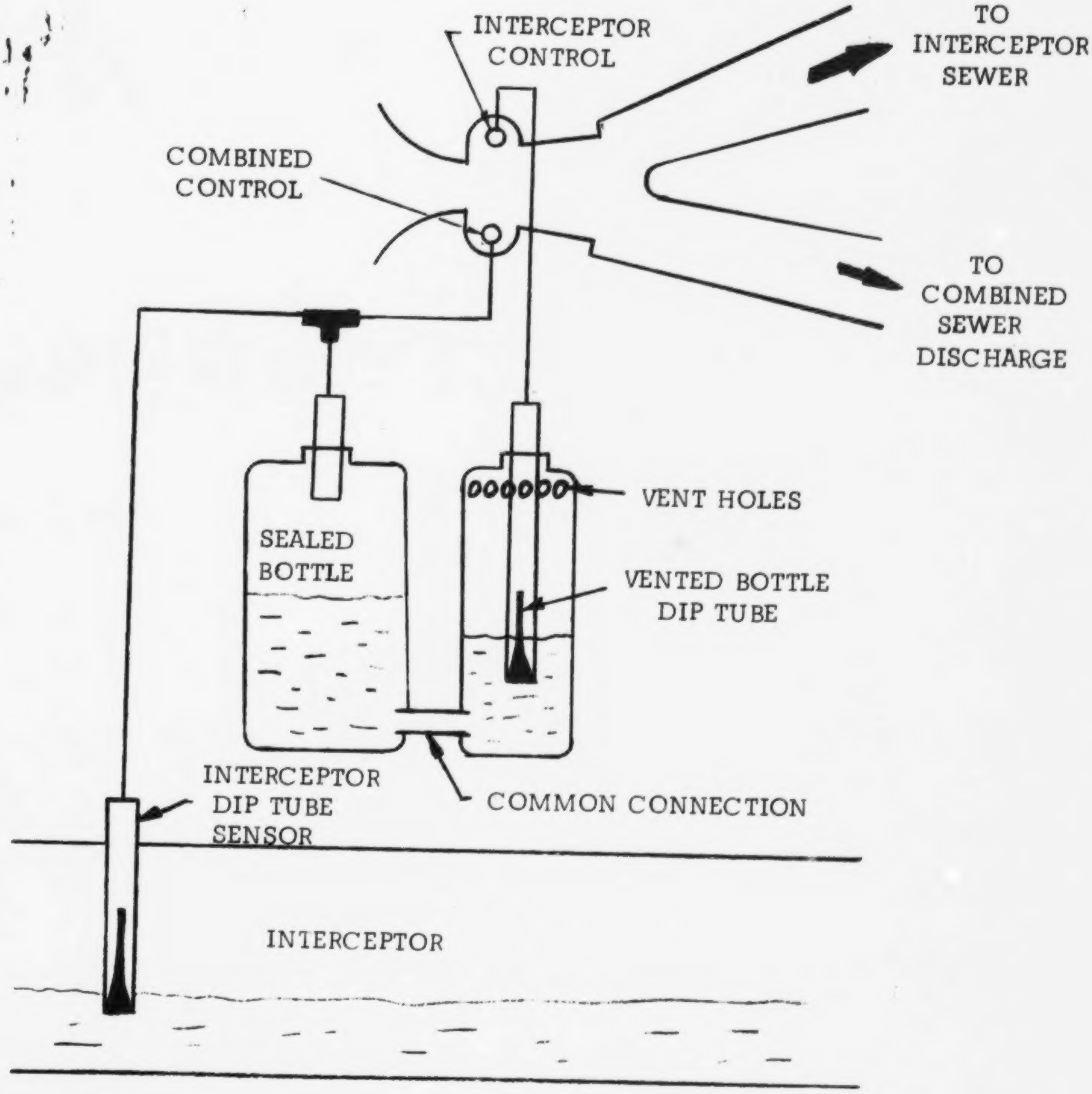

INTERCEPTOR CONTROL
TO INTERCEPTOR SEWER
COMBINED CONTROL
TO COMBINED SEWER DISCHARGE
SEALED BOTTLE
VENT HOLES
VENTED BOTTLE DIP TUBE
INTERCEPTOR DIP TUBE SENSOR
COMMON CONNECTION
INTERCEPTOR

Figure 66. No-Moving-Part Sensor Test Setup

Push-Pull Sensor Tests. Several tests were made to investigate the no-moving-part bottle sensor with different dip tubes and bottles, see Figures 67 and 68. It was found that equal size bottles with equally distributed dip tube areas did not provide enough gain and control was very non-linear. A sealed bottle of twice the area of the vented bottle was tried to increase sensor gain; however, this was only partially successful. Control with the push-pull bottles as a function of interceptor water level did not affect diversion until the dip tube sensor was over 50% closed; however, after diversion control started a reasonably linear control range was observed, see Figure 69. In order to expand the control range the interceptor dip tube was shaped similar to Sensor #1 shown in Figure 60; however, no noticeable improvement in performance was observed.

After testing of model sewer regulators was completed and aspirated air flow data analyzed it was found, as shown in Figure 70, that the aspirated air flow is high at the midpoint in diversion (see Appendix C for actual data curve) and drops sharply as diversion approaches its maximum value. Thus, only a low aspiration capability is available to produce the initial change in the fluid levels of the push-pull sensor bottle to obtain linear analog control. From a controls system standpoint, this characteristic represents a region of very low gain. Therefore, to provide linearity, this low gain region must be compensated by a high gain in some other part of the system. The two-bottle, or U-tube concept offers several approaches to provide such a localized, high gain characteristic.

1. The dip tube orifices can be shaped so that a small change in liquid level effects a large change in total orifice area. This requires a non-linear tapered slot, which widens abruptly near the bottom of its range.

2. The relative bottle diameters can be shaped. The increase in vacuum on the combined port as the interceptor sensor is covered causes a corresponding differential change in the liquid level between the U-tube branches. Since only a fixed amount of liquid is involved, the relative fluid level rise in the closed branch, as compared to the level drop in the vented branch, is proportional to the inverse ratio of the branch cross section areas. Thus if the vented branch is necked down opposite the bottom end of the dip tube slot, a relatively large change is liquid level will result from a small increase in vacuum.

It was not possible to fully explore the above possibilities within the scope of this initial program phase; however, it appears certain that good diversion linearity can be achieved through one or both, so that proper sewer regulation without moving mechanical parts is achieved.

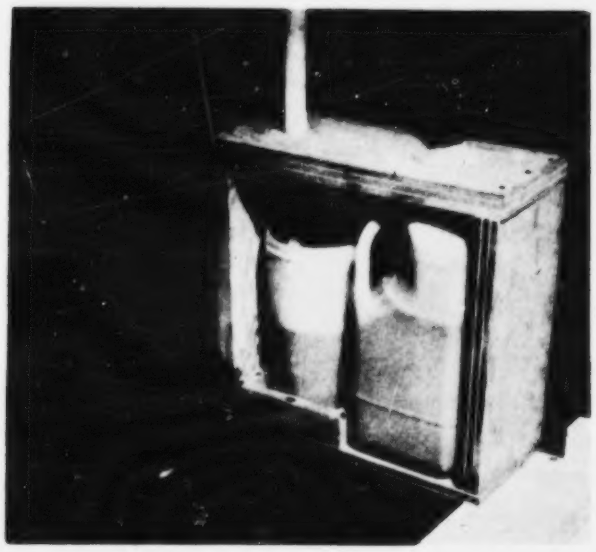


Figure 67. No-Moving-Part Sensor Push-Pull Bottles

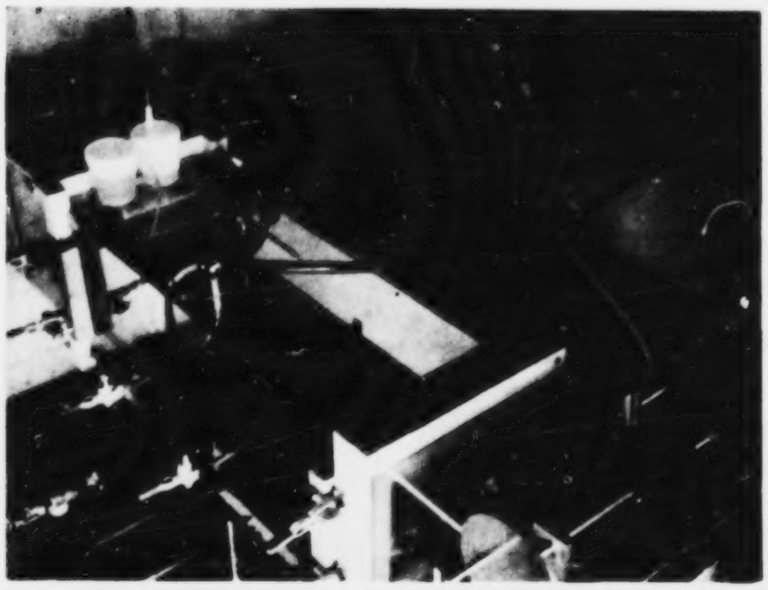


Figure 68. No-Moving-Part Bottles Installation

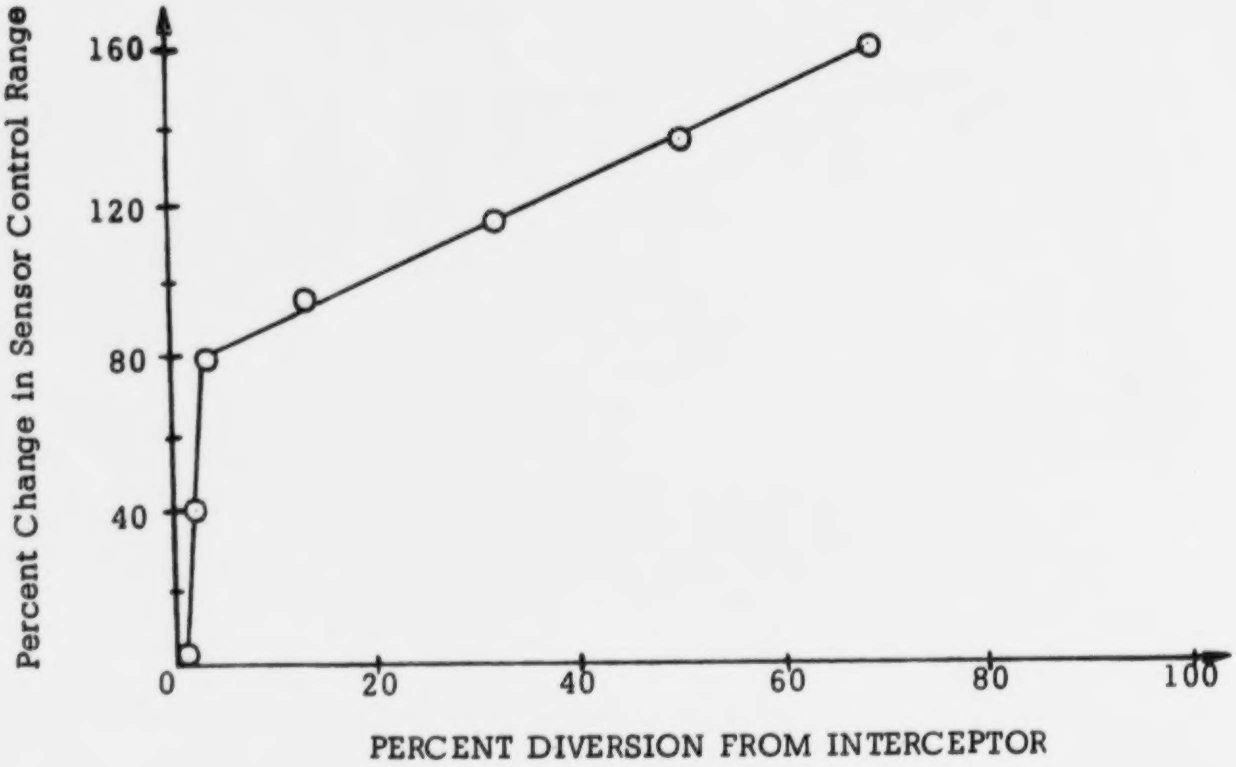


Figure 69. Diversion vs Control for No-Moving-Parts Push-Pull Sensor Nozzle 2" x 4"

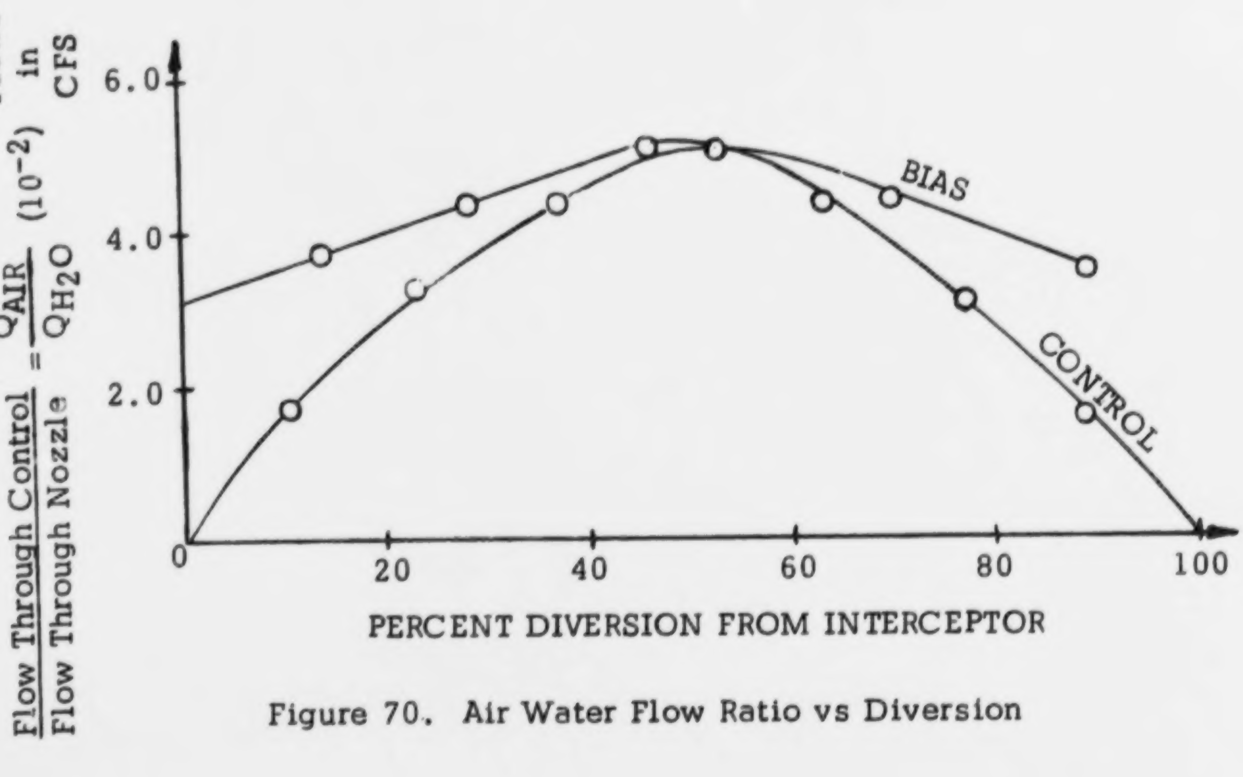


Figure 70. Air Water Flow Ratio vs Diversion

Multiple Sensors

In an effort to determine whether two fluid levels could be monitored with dip tube sensors and added to provide control from a single control port, the sensor combination shown in Figure 71 was tested. In this setup one dip tube sensor was put upstream of the regulator nozzle in the combined sewer and a second sensor was placed in the interceptor sewer. Both sensors were then connected to the combined control to provide diversion control. With the knowledge of the optimum area for analog control as discussed above the total area of both sensors was selected having an area ratio of about 3:1. The diversion performance of the multiple sensors was measured as a function of supply head. Curve 1 of Figure 72 shows the change in diversion vs head over the full range of the combined sensor with the interceptor level constant. Curve 2 of Figure 72 shows the change in diversion resulting from change in head without the combined sewer sensor connected to the control. The significant difference between these curves shows that both sensors are contributing to the diversion. Figure 73 consists of a similar pair of curves taken at a different interceptor water level. Results of these tests showed that the knowledge of control areas obtained from regulator tests could be applied to multiple dip tubes as well as single ones.

Flow-Over Discharge

Diversion performance of the sewer regulator was tested for the simulated condition of large upstream heads, caused by storm flows, causing flow over the regulator and thus over the discharge. When the head of water flowing over the discharge exceeds about fifteen (15) percent of the upstream head the fluidic regulator flow is biased to the interceptor and diversion performance is seriously reduced. In an effort to avoid this problem, shrouded discharge tests were made to isolate the two flows and provide an air-water mixing region, see Figures 74 and 75. For large flows over the regulator a short shroud will act like a leaping weir; however, at low flows a short shroud produced interference, see Figure 74, and effected diversion noticeably. A longer shroud as shown in Figure 75 solved this problem.

From these tests it is concluded that for installations where the outfall communicates to tidal waters or back water conditions exist to produce a head at the outfall the fluidic regulator performance will show significant degradation as the discharge head builds to about fifteen (15) percent of the supply head regardless of shrouding.

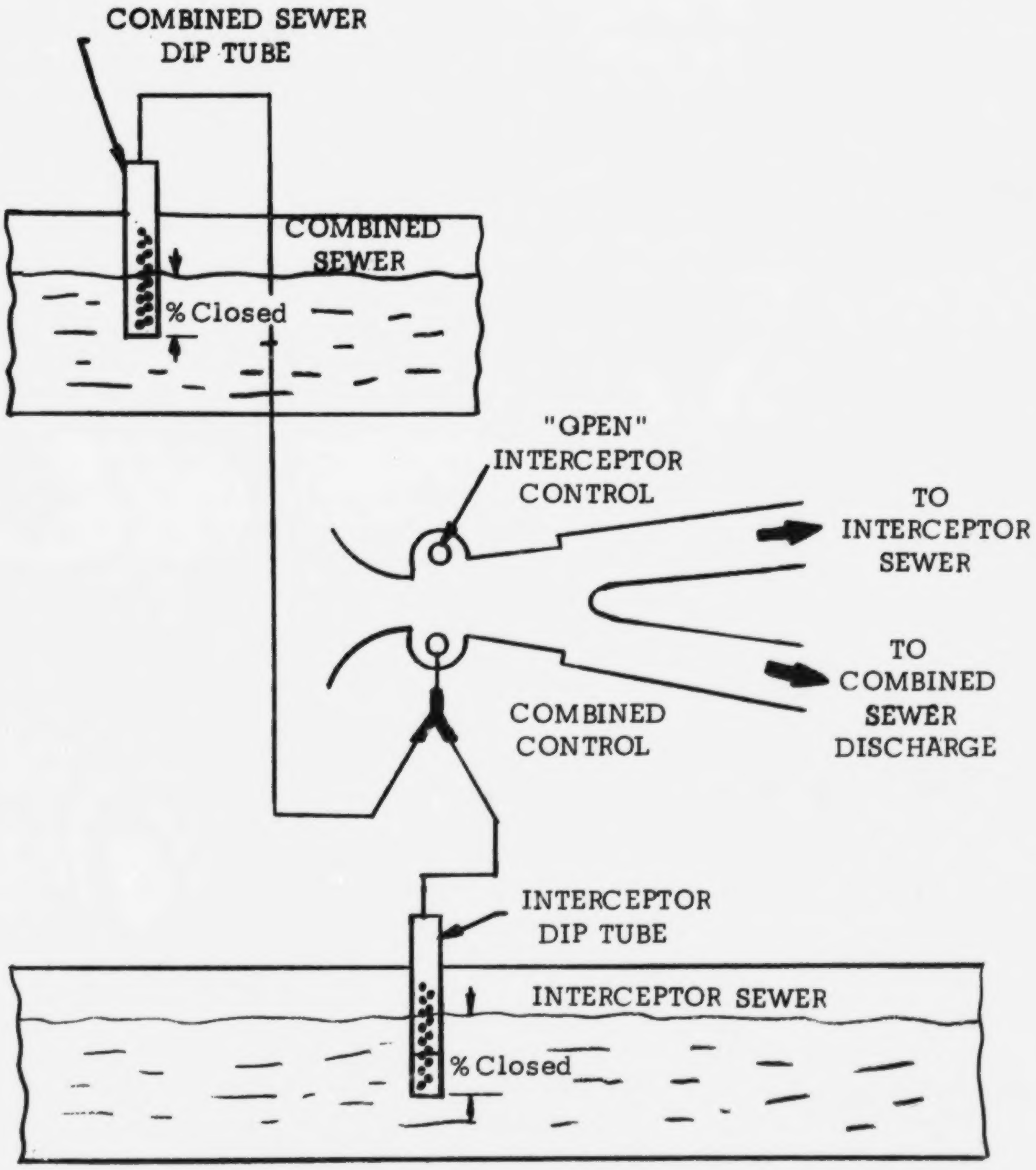

COMBINED SEWER
DIP TUBE
COMBINED
SEWER
% Closed
"OPEN"
INTERCEPTOR
CONTROL
TO
INTERCEPTOR
SEWER
TO
COMBINED
SEWER
DISCHARGE
COMBINED
CONTROL
INTERCEPTOR
DIP TUBE
INTERCEPTOR SEWER
% Closed

Figure 71. Multiple Sensor Test Setup

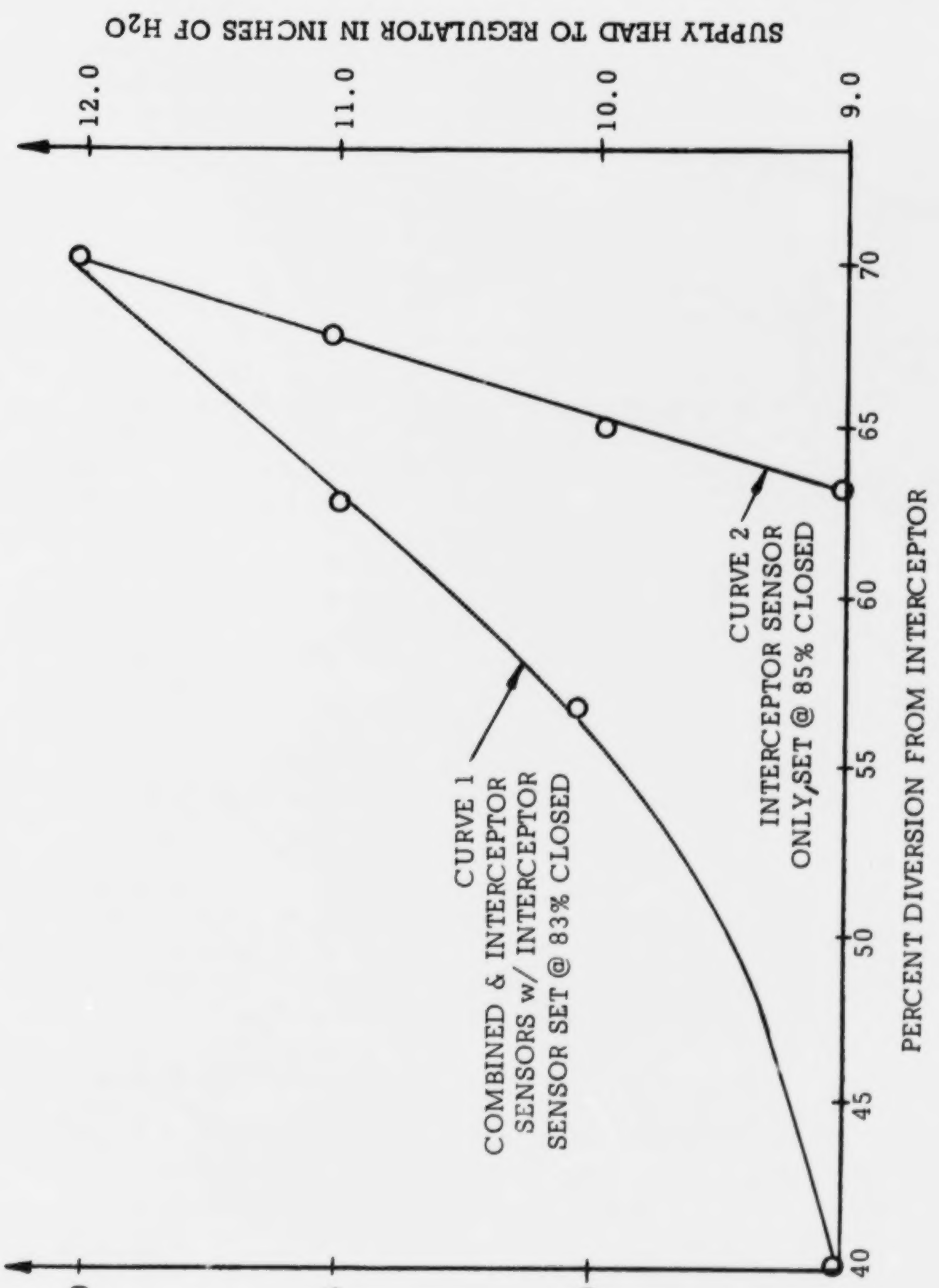


Figure 72. Diversion vs Supply Head for Multiple Sensor Control of Fluidic Sewer Regulator

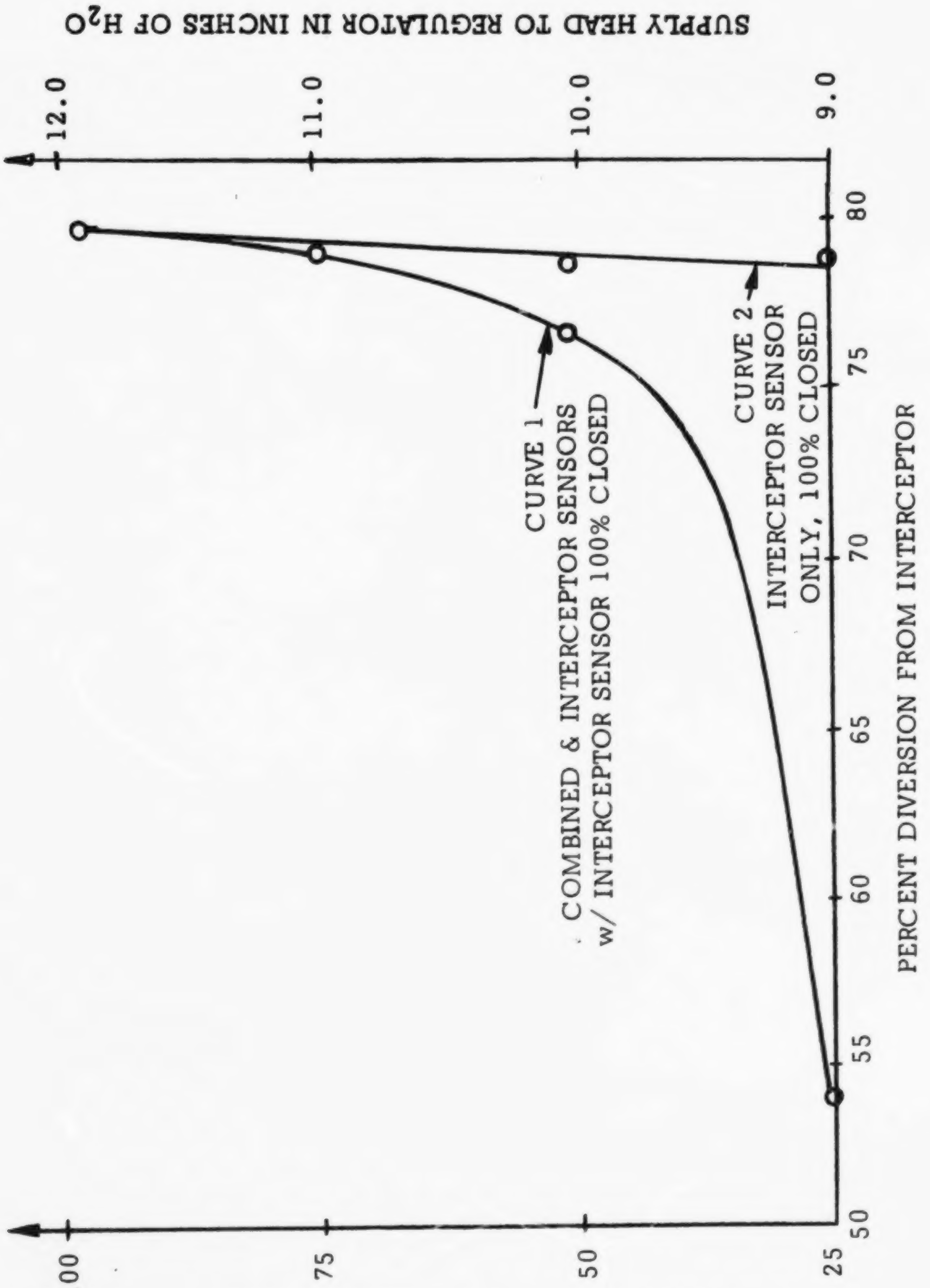


Figure 73. Diversion vs Supply Head for Multiple Sensor Control of Fluidic Sewer Regulator

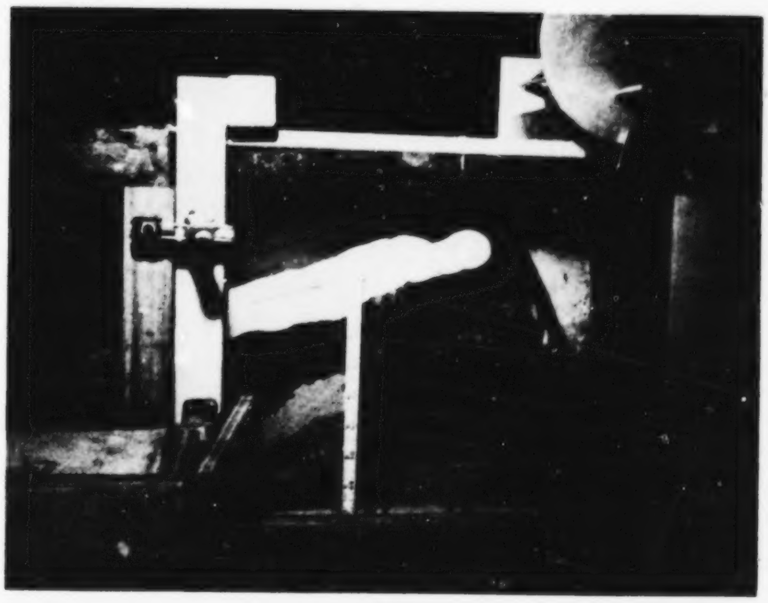


Figure 74. Shrouded Discharge Low Velocity Flow Interference

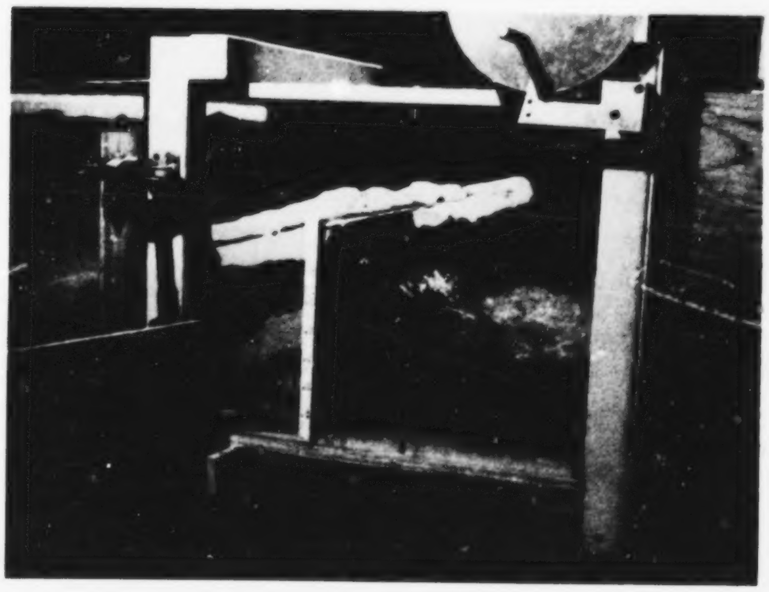


Figure 75. Shrouded Discharge Low Velocity Longer Shroud
No Interference

Fouling Analysis

In order to determine a Fluidic regulator's susceptibility to fouling, tests were conducted with small branches of various sizes and shapes. Maximum dimensions of branches ranged from 1.1 to 4 times the nozzle height (h_n), as shown in Figure 77. The channel upstream of the nozzle was 6 h_n square so branches could approach in any orientation. The regulator used for testing is shown in Figure 76. Ten runs were made with each of eight branches giving a total of 80 runs. Six cases of lodged branches occurred, three on the converging section of the nozzle and three on the splitter. The splitter in this case was relatively sharp making it more susceptible to fouling by the forked sticks than other regulator splitter geometries having the same functional characteristics; see Appendix D for fouling data. In addition to tests with branches, tests were run with pieces of paper to give some insight into the fouling caused by large soft objects such as newspapers. No problems were experienced except with a very large, 5 h_n x 8 h_n piece which caught 2 of 6 times on the pointed splitter. Later tests showed that regulators with blunted splitters could be designed to perform as well as pointed splitter types, therefore actual hardware utilizing blunted splitter designs will be less subject to fouling.

Fouling tests showed that the Fluidic sewer regulator without an upstream trap of any sort was relatively free of fouling. On the occasions when fouling occurred, the fouling objects had a linear dimension of four (4) or more times the nozzle height. A sharp splitter is more susceptible to fouling than a blunt one, and that sharp corners near the regulator nozzle should be well beveled, or rounded.

It is anticipated that field tests to be conducted as part of the demonstration grant will resolve the fouling problems associated with fluidic sewer regulators under actual conditions.

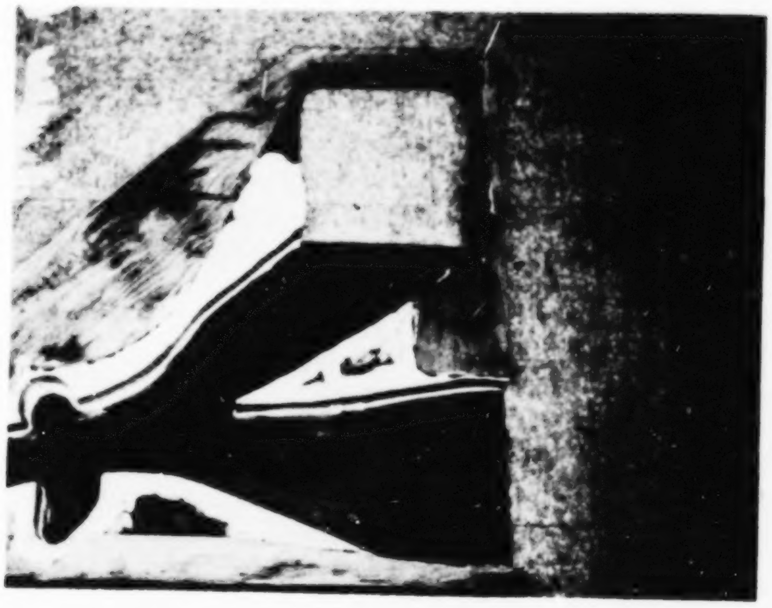


Figure 76. Basic Irrigation Test Model
2" x 3" Nozzle

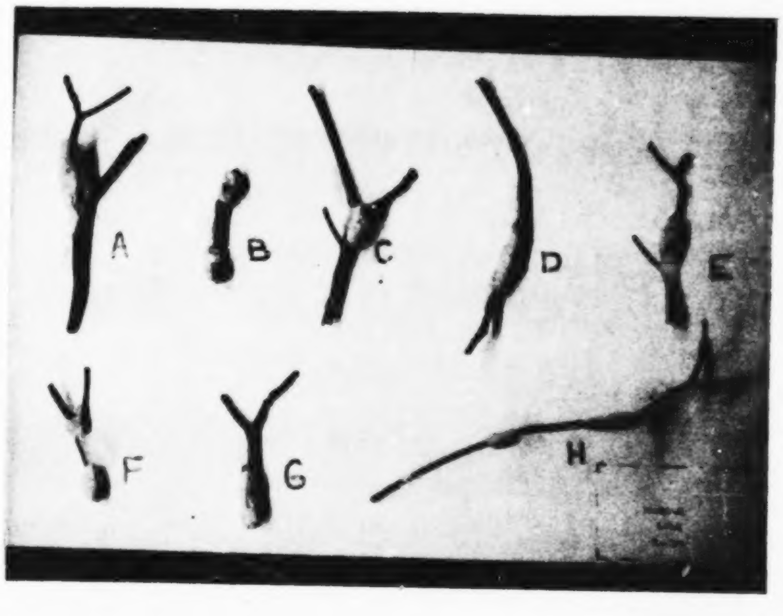


Figure 77. Simulated Debris, Fouling Test

SECTION 6

DEMONSTRATION PLANNING AND LIAISON

General

One of the specific objectives of the subject program was to assist the FWPCA in planning and establishing the succeeding phases of the program; namely, the design, construction, operation, and evaluation of the Fluidic Sewer Regulator concept in a typical metropolitan diversion location. It is the FWPCA's intent that the work should be done by a large municipality, under a FWPCA Demonstration Grant. Because of the preponderance of combined sewers in the eastern USA and the relative convenience in performing engineering liaison from both BEC and the FWPCA, it was decided that candidate cities should be New York, Chicago, Washington, D. C., Philadelphia, and Baltimore.

Accordingly, a series of visits were arranged with the various municipal sewer engineering chiefs as follows:

City	Official & Title	Date
New York City, N.Y.	Mr. Joseph Cunetta Deputy Director, Plants Bureau of Water Pollution Control City of New York	July 8, 1969
Chicago, Illinois	Mr. Clint Keifer Chief, Water & Sewer Design Engr'g, Dept. of Public Works City of Chicago	July 14, 1969
Baltimore, Maryland	Mr. John Prussing Principal Engineer Sewer Construction	July 25, 1969
Philadelphia, Pa.	Mr. Carmen Guarino Deputy Water Commissioner City of Philadelphia	July 28, 1969
Washington, D. C.	Mr. James Robertson Associate Director Engr'g & Construction Dept. Sanitary Engr'g District of Columbia	August 5, 1969

Questionnaire

A brief questionnaire was presented at each meeting to assist in defining each city's capability and interest in seeking and performing the subject Fluidic regulator demonstration uder a FWPCA Demonstration Grant. The questionnaire contained the following:

1. Are relatively small diversion points available within the municipal area for installing a small pilot model Fluidic sewer regulator?

2. Is municipal funding available in keeping with the FWPCA's 75% - 25% funding policy?

3. Are there difficulties, or unusual conditions required to secure the commitment of municipal funds to support 25% of the program cost?

4. Would serious scheduling delays exist in the installation of the demonstration program due to prior commitment, or unavailability of engineering or construction manpower, or facilities?

5. Would the municipality consider the use of A&E contract assistance in conducting the demonstration program?

6. Would the municipality encounter procurement difficulties in contracting for sole source goods or services in view of BEC's proprietary position in the Fluidic field in general, and in water management devices in particular?

7. Has the municipality had prior experience in conducting programs under FWPCA Research, or Demonstration Grants?

8. Would officials of the municipality be interested in visiting BEC's laboratory and watching a demonstration of the experimental model?

Visit Discussion

The results of each visit are summarized:

New York City. Mr. Cunetta and his staff showed strong technical interest in the program concept, and test results. Questions were raised on the effect of regulator diversion performance away from interceptor when tide gates are backloaded with high tides; Answer - regulator would work fairly well until tide level exceeded 25% of inlet head level. In response to questionnaire items:

1. Location for small regulators probably available, but some study needed.

2. Funds could be made available, with approval of Board of Estimates.

3. No specific approval difficulties - this type of program has been approved in the past.

4. A starting delay from 18-24 months would be necessary due to engineering work backlog.

5. NYC would consider A&E assistance; they suggest that BEC should contract this effort directly, rather than NYC.

6. No specific problem procuring sole source, proprietary equipment or services if good reason is present.

7. NYC is currently evaluating the "Ponsar" regulator concept under FWPCA Demonstration Grant.

Summary -- New York City has the technical interest, and financial capability, but engineering capability would not be available for 1-2 years - Good possibility for a Demonstration Grant program later, poor possibility in near future.

Chicago, Illinois. Mr. Keifer showed moderate technical interest in concept, but indicated that Chicago's system of sewers did not include many small diversion points that needed regulation (most regulation is done with very large electric motor driven gate structures), and foresaw difficulty in getting approval to install a regulator in a currently non-regulated diversion point. In response to questionnaire items:

1. Small diversion points available, but currently do not need regulation (see above).

2. Present bond improvement funds very low - more bonds require voter approval before a new program could be committed.

3. No particular difficulty in funding programs of this magnitude if funds are available.

4. No particular difficulty in getting approval, if funds are available.

5. Chicago would probably not use A&E assistance for basic hydraulic design - only for detailed structures once specifications are established.

6. No difficulty in sole source, proprietary procurement of equipment, or services, if good reason is present.

7. Chicago currently has several FWPCA Demonstration Grant programs in progress.

Summary -- Chicago has an excellent technical capability for the subject program, but currently no firm requirements for this device; is very limited in available funds - poor immediate possibility for the subject Demonstration Grant program.

Baltimore, Maryland. Mr. Prussing showed technical interest but indicated that Baltimore had virtually no combined sewers. He indicated that requirements for storm water diversion existed, if the device could be adapted to this requirement (Answer - it could). In response to the questionnaire:

1. Except for a few storm water diversion points, very few diversion points are available.

2. Municipal funding is available.

3. No particular difficulties in obtaining approval of Board of Estimates.

4. Baltimore has a significant engineering work backlog. Consequently, considerable delay in starting would be anticipated.

5. A&E contract assistance would be a strong probability.

6. No difficulty in procurement of proprietary, sole source equipment, or services if justification shown.

7. Baltimore currently has a FWPCA Demonstration Grant program in progress at the Back River Sewage Treatment Facility.

Summary -- Baltimore has minimum requirements for subject device, except possibly for storm water handling. Despite general technical interest, this city has a considerable engineering work backlog, and thus could not consider the subject demonstration program for a considerable period of time - poor possibility for the near future.

Philadelphia, Pennsylvania. Mr. Guarino showed strong interest both in the technical progress made to date, and, the possibility of evaluating the concept. Philadelphia has at present approximately 70 small mechanical float-operated regulators, in addition to a number of large hydraulically operated units. The small units require at least twice-a-week surveillance and close monitoring during storm conditions to keep them operating. With this background, Mr. Guarino indicated he was quite interested in evaluating approaches which might require less monitoring. With respect to the questionnaire items:

1. Philadelphia has a considerable number of mechanical regulators, also many "slot" diverters, which are basically equivalent to the standard diversion dam and interceptor side flow line arrangement.

2. Municipal funding is readily available for experimental purposes upon the approval of the Water Commissioner.

3. Funding approval can be made directly by the Water Commissioner.

4. Philadelphia has an experienced engineering staff who would be available on short notice to undertake the subject program.

5. A&E support would be considered, but is probably not specifically required.

6. There would be no procurement difficulty for sole source, or proprietary equipment or services, if sufficient justification is present.

7. Philadelphia is currently active on a FWPCA Demonstration Grant concerning microstrainers for combined sewer overflows.

Summary -- Philadelphia appears to have strong interest, and excellent capability for performing the subject Demonstration Program - A top possibility.

Washington, D. C. Mr. Moorehead, acting for Mr. Robertson, indicated a strong interest in the Fluidic concept, having accepted an invitation to view the experimental model at BEC's laboratory in the D.C. area where a pilot Fluidic regulator could be demonstrated. However, he cited local government policy which forbade any new construction, or improvements to be made on existing combined sewers, since the city was embarked on a long term program to replace these with separate sewers. Consequently, although the city would be willing to offer a location for a demonstration model, it would not agree to conduct the actual demonstration program under a FWPCA grant.

Summary -- Despite a strong technical interest in the subject concept, and a very cooperative attitude in offering to provide facilities and other assistance to such a demonstration program, Washington, D. C. could not be considered for the subject program.

Second Round Meeting

Following the initial series of meetings, Mr. Guarino and his staff visited BEC on September 3 and viewed the experimental laboratory model. Mr. Guarino confirmed the City of Philadelphia's desire to participate in the subject Demonstration Grant program. At the time of writing of this report, the Demonstration Grant Request is in preparation by his staff.

Demonstration Program Schedule

A preliminary Demonstration Program Schedule spanning 24 months is shown in Figure 78. This plan would establish a 4 month design phase, a 4 month construction phase, a 2 month checkout phase, and a 12 month operational evaluation phase, and a 2 month reporting phase. This plan will be finalized when the Demonstration Grant Request is submitted to the FWPCA.

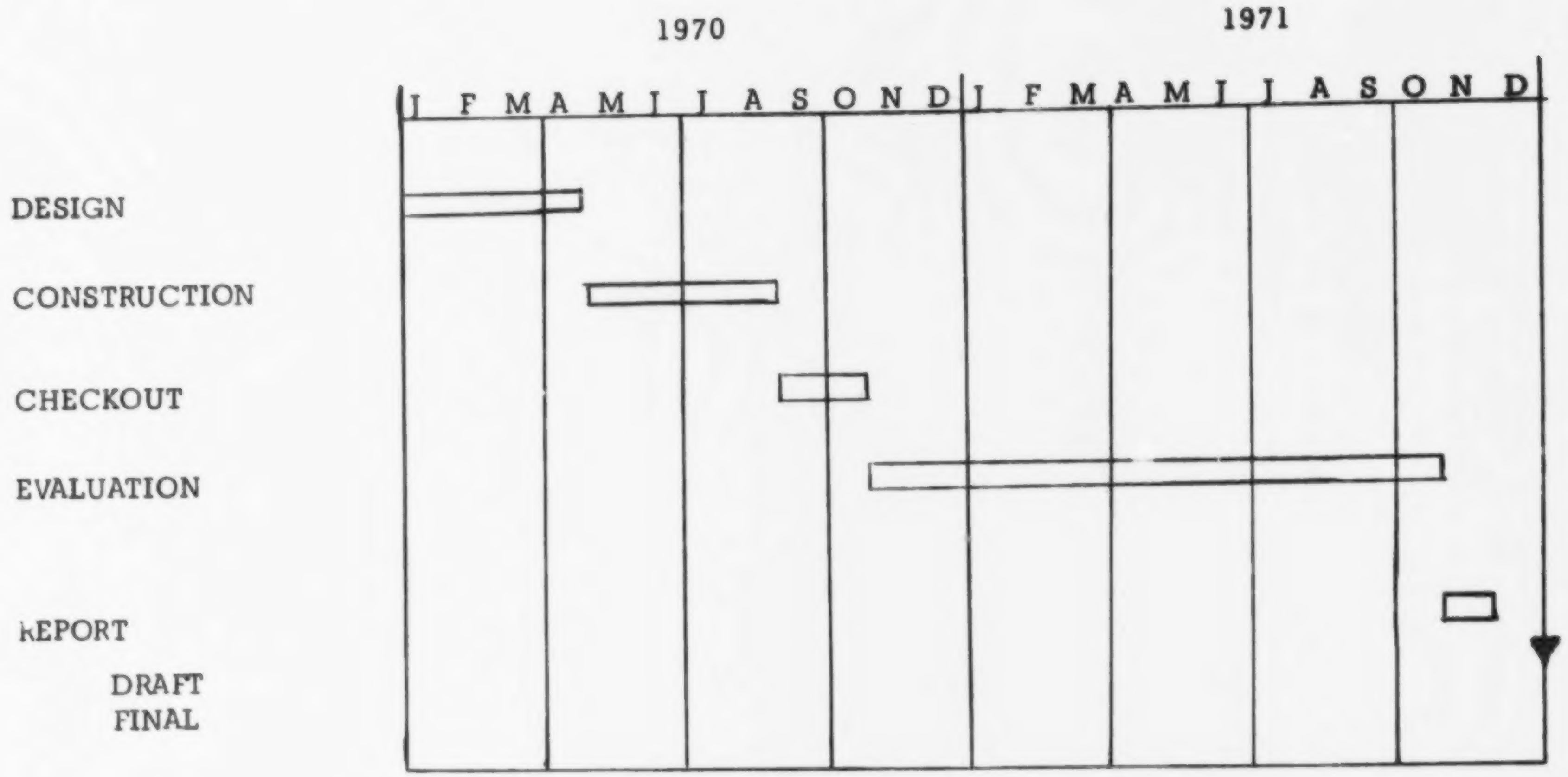


Figure 78. Preliminary Demonstration Plan

SECTION 7

ACKNOWLEDGEMENTS

Acknowledgement is made to the following chiefs of Sewer Engineering, and their respective staffs, for their interest and the time taken in the conducting of the interviews necessary for the Demonstration and Planning phase of the subject program, as described in Section 6.

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Mr. John Prussing
Principal Engineer
Sewer Construction
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Mr. Carmen Guarino
Deputy Water Commissioner
City of Philadelphia

Mr. James Robertson
Associate Director
Engr'g & Construction
Dept. of Sanitary Engr'g
District of Columbia

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Acknowledgement is made to members of the Bowles Engineering Corporation staff as follows:

P. A. Freeman	Program Director
R. Bean	Research Engineer
J. Zaloudek	Research Engineer
P. Cain	Test Technician
P. Senes	Test Technician
A. Freiling	Model Shop

SECTION 8

REFERENCES AND PUBLICATIONS

1. Report: "Problems of Combined Sewer Facilities and Overflows - 1967," prepared by the APWA under contract 14-12-65, sponsored by the FWPCA.

2. Paper: "Performance and Operating Characteristics of a Fluidic Irrigation Diverter," prepared by Drs. Howard R. Haise and E. Gordon Kruse, of the ARS, SWC, USDA, Ft. Collins, Colorado.

3. Article: "Air Pressure Drop Nomograph," F. Kaplan, Kaiser Engineers, appearing in the April 1967 issue of Controls Engineering Magazine.

SECTION 9

GLOSSARY OF TERMS AND ABBREVIATIONS

Fluidic Element Nomenclature

Nozzle - opening where fluid (water in this case) enters the fluidic element having a geometry similar to a venturi throat.

Control Ports - openings immediately downstream from the nozzle, where fluid (gas or liquid) is admitted to influence the direction of nozzle flow.

Interaction Area - the volume of the element immediately downstream of the control ports and upstream of the splitter, containing the attachment walls.

Splitter - a wall which divides the fluidic element exit area into two (or sometimes more) sections.

Attachment Walls - wall of element immediately downstream of the control pockets to which the water jet attaches by the coanda effect.

Coanda Effect - wall attachment phenomenon of a jet stream close to a wall which provides a pressure differential to act on the jet stream as a result of entrainment at the wall, producing a low pressure area.

Venturi - a constriction in a flow channel which produces increased velocity and decreased pressure or suction at the constriction.

Aspiration - drawing of fluid (air in this case) into diverter interaction region by suction caused by the venturi action of nozzle.

Setback - offset of one portion of geometry to another measured away from centerline of nozzle.

Aspect Ratio - ratio of height of diverter nozzle to its width.

Digital Switching - having only two functional states, either maximum or minimum diversion.

Analog Switching - having a continuous range of diversion values between maximum and minimum levels.

Abbreviations

PVC - Polyvinylchloride

ABS - Acrylonitrile - Butadiene - Styrene

PE - Polyethylene

h_n - height of regulator nozzle

h_i - height of inlet head

h_d - height of discharge

w_n - width of regulator nozzle

a - aspect ratio

A_N - area of nozzle

SECTION 10

APPENDICES

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APPENDIX A

Log of Sewer Regulator Element Tests

The test program was begun with tests of the 1/2" x 1/2" nozzle irrigation diverter as part of the task 1 predictive analysis listed on the first page. Testing was then continued on model sewer regulator variations starting from the basic irrigation geometry, and culminating in the final analog regulator configuration. These tests are listed from June 20 to July 25. Several final configurations were then tested to investigate minor changes in geometry and obtain performance curves and design data (see tests from August 15 to September 4). Tests listed in the log were for regulator elements for which test data were recorded and a definite variable was tested. In many cases numerous testing was done by visual observation with many variables and formal data were not recorded.

Log of Sewer Regulator Element Tests

Test Date	Test No.	Config. No.	Nozzle Size	Sensor	Parameter Tested	Results of Tests	Diversion Range
4-4	1	Irrigation Element	1/2x1/2	Bias Orifices	Supply Flow vs Head	Useful productive data	0-100
4-7	1	Irrigation Element	1/2x1/2	Bias Orifices	Control Flow vs Supply Flow	Useful productive data	0-100
4-9	1	Irrigation Element	1/2x1/2	Bias Orifices	Control Biases	Some analog control possible	50-100
4-17	1	Irrigation Element	1/2x1/2	Bias Orifices	Head = 3.0" Control Biases	Digital operation	0-70
4-17	2	Irrigation Element	1/2x1/2	Bias Orifices	Head = 5.0" Control Biases	More analog range	0-95
4-17	3	Irrigation Element	1/2x1/2	Bias Orifices	Head = 7.5" Control Biases	Same as 5.0" head	0-90
4-18	1	Irrigation Element	1/2x1/2	Bias Orifices	Head = 3.0" Zero set back	No control	95-98
4-18	2	Irrigation Element	1/2x1/2	Bias Orifices	Head = 4.0"	No control	95-100
4-18	3	Irrigation Element	1/2x1/2	Bias Orifices	Head = 7.5"	No control	95-100
4-24	1	Irrigation Element	1/2x1/2	Bias Orifices	Control Airflows	Airflow vs % div. obtained	0-95
4-24	2	Irrigation Element	1/2x1/2	Bias Orifices	Control Pressures	Pressure diff. vs. Diversion obtained	0-95
4-28	1	Irrigation Element	1/2x1/2	Bias Orifices	Setback	Curve obtained low scatter of data	0-100
4-28	2	Irrigation Element	1/2x1/2	Bias Orifices	Control Airflow	Airflow vs % div. showed wide scatter	0-95

Log of Sewer Regulator Element Tests (Continued)

Test Date	Test No.	Config. No.	Nozzle Size	Sensor	Parameter Tested	Results of Tests	Diversion Range
5-14	1	513-1	2x3	Bias Orifice	Single control geometrical bias	Poor control range	25-45
5-14	2	513-1	2x3	Bias Orifice	Weir setting	Poor control range	16-36
5-14	3	514-1	2x3	Bias Orifice	Cusp on splitter	Improved diversion range	19-73
5-15	1	515-1	2x3	Bias Orifice	Cusp - smaller	Reduced operating range	27-39
5-16	1	516-1	2x2-1/2	Bias Orifice	Irrigation Geometry	Strickly bistable operation	8-100
5-16	2	516-2	2x3-1/4	Bias Orifice	Wider nozzle pointed splitter	Improved diversion range	20-79
5-23	1	516-2	2x3-1/4	Bias Orifice	Weir setting	Good range - still bistable	15-94
5-26	1	516-2	2x3-1/4	Bias Orifice	Lower head	Reduced range	23-88
5-29	1	527-1	2x3-1/4	Bias Orifice	Fouling tests	Low percent fouling	18-87
6-16	1	616-1	2x1	Bias Orifice	Higher aspect ratio	Comparable to previous tests	18-80
6-16	2	616-2	2x1	Bias Orifice	Smaller control pockets	Strickly bistable	18-79
6-17	1	617-1	2x1	Bias Orifice	Vortex pockets 1-1/2"	Some intermediate values	0-100
6-17	2	617-2	2x1	Bias Orifice	Vortex pockets 2"	Poor control	30-78
6-18	1	618-1	2x1	Bias Orifice	Increased set-back decreased wall angle	Reduced operating range	26-64
6-18	2	618-2	2x1	Bias Orifice	Splitter position 1" downstream	Same as 618-1	27-68
6-18	3	618-3	2x1	Bias Orifice	Vortex pockets 3"	No control	50-50
6-18	4	618-4	2x1	Bias Orifice	New profile cutaway sidewalls	Nearly bistable	15-74
6-19	1	618-4	2x1	Float Valve	Sensor	Small analog range	30-91
6-19	2	618-4	2x1	Bottles	Sensor	Sames as Test 1 above	30-100
6-19	3	618-4	2x1	Bias Orifice	Sensor	Reduced operating range	30-68

Log of Sewer Regulator Element Tests (Continued)

Test Date	Test No.	Config. No.	Nozzle Size	Sensor	Parameter Tested	Results of Tests	Diversion Range
6-20	1	620-1	2x1	Bias Orifice	Setback = 0	Not enough setback to deflect jet	50-50
6-20	2	620-2	2x1	Bias Orifice	Splitted moved upstream	Same as Test 1 above	50-50
6-20	3	620-3	2x1	Float Valve	Setback increased	Same as Test 1 above	50-50
6-20	4	620-4	2x1	Float Valve	Short sidewalls added	Improved analog control range	0-77
6-20	5	620-5	2x1	Bottles	Short sidewalls	Pour range - surging	0-81
6-23	2	623-1	2x1	Float Valve	Wall length 1.2"	Poor range	11-52
6-23	3	623-3	2x1	Float Valve	Wall length 3.2"	Improved range	19-100
6-23	4	623-4	2x1	Float Valve	Splitter moved 2" downstream	Reduced operating range	8-71
6-24	1	624-1	2x1	Float Valve	Curved sidewalls 1.2"	No significant improvement	11-83
6-24	2	624-1	2x1	Float Valve	Control orifice shade	Slightly improved linearity	15-86
6-24	3	624-1	2x1	Float Valve	Larger area triangle	Most linear performance	12-83
6-24	4	624-1	2x1	Float Valve	One half size triangle	Much more digital performance	13-75
6-25	1	625-1	2x1	Float Valve	Pointed splitter upstream	Improved range	11-79
6-25	2	625-2	2x1	Float Valve	Blunt splitter	Reduced range	10-45
6-26	1	626-1	2x1	Float Valve	Splitter moved downstream	Improved range	6-73
6-26	2	626-2	2x1	Float Valve	Sharp splitter	Suring - splitter very close	7-100
6-26	4	626-4	2x1	Float Valve	Sidewall cutback shortened 1/2"	Not surging	11-91
6-26	5	626-5	2x1	Float Valve	Rounded splitter	Reduced range	19-81
6-27	1	627-1	2x1	Float Valve	Sidewall cutback shortened 1/8"	Improved range	0-86
7-1	2	71-1	2x4	Float Valve	Nozzle	Did not match 2x1 performance	4-68
7-1	3	71-1	2x4	Float Valve	Combined weir raised	Improved range	7-81

Log of Sewer Regulator Element Tests (Continued)

Test Date	Test No.	Config. No.	Nozzle Size	Sensor	Parameter Tested	Results of Tests	Diversion Range
7-8	1	74-1	2x4	Float Valve 1	Sensor low head	Poor control	35-54
7-8	2	74-1	2x4	Float Valve 1	Interceptor weir lower	Slight increase in range - digital	3-40
7-8	3	74-1	2x4	Float Valve 1	Increased head 10"	Improved range - digital	4-61
7-9	1	78-1	2x4	Float Valve 1	Interceptor weir higher	Improved range - digital	5-70
7-9	2	78-1	2x4	Float Valve 1	Increased head 13"	Slightly improved - digital	1-69
7-9	4	78-1	2x4	Float Valve 1	Lower head 8.5"	Reduced range - digital	3-55
7-9	5	78-1	2x4	Float Valve 1	Low head 60"	Further Reduced range	2-47
7-10	1	710-1	2x4	Float Valve 1	Head 8.5"	Still digital	1-78
7-10	2	710-1	2x4	Float Valve 1	Head 10.0"	Same as 8.5" head	1-75
7-10	3	710-1	2x4	Float Valve 1	Head 12.0	Same as 8.5" head	1-78
7-10	4	710-1	2x4	Float Valve 1	Head 6.0	Greatly reduced range	1-38
7-11	1	710-1	2x4	Float Valve 2	Sensor head 10.0"	Increased analog range	2-76
7-11	2	710-1	2x4	Float Valve 2	Lower combined weir	Reduced range	5-58
7-11	3	710-1	2x4	Float Valve 2	Increased head 13.0	Sames as 8.5" head	2-79
7-11	4	710-1	2x4	Float Valve 2	Head 7.5"	Reduced range	0-60
7-11	5	710-1	2x4	Float Valve 3	Sensor head 10.0"	Analog performance	0-74
7-14	1	710-1	2x4	Float Valve 2M	Sensor head 8.5"	Linear analog performance	3-69
7-15	1	710-1	2x4	Float Valve 2M	Head 11.0"	Increased range	2-81
7-15	2	710-1	2x4	Float Valve 2M	Head 14.0"	Reduced range	3-47
7-15	3	710-1	2x4	Float Valve 2M	Raised combined weir	Range restored	3-81
7-15	4	710-1	2x4	Float Valve 2M	Reduced head 11.0"	Reduced range	1-69

Log of Sewer Regulator Element Tests (Continued)

Test Date	Test No.	Config. No.	Nozzle Size	Sensor	Parameter Tested	Results of Tests	Diversion Range
7-16	1	710-1	2x4	Float Valve 2M	Head 10.0	Linear	3-77
7-16	2	710-1	2x4	Float Valve 2M	Head 13.0	Increased range	3-81
7-16	3	710-1	2x4	Float Valve 2M	Head 6.5	Reduced range	8-53
7-16	5	710-1	2x4	Float Valve 2M	Head 6.0	Greatly reduced range	4-8
7-16	6	710-1	2x4	Float Valve 2M	Head 7.0	Increased range	5-53
7-18	1	710-1	2x4	Multiple Dip tubes	Sensors	Poor control range	5-26
7-18	2	710-1	2x4	Single Dip tube	Sensor	Wide linear control	1-76
7-18	3	710-1	2x4	Multiple Dip Tubes	Sensor areas	Good range - linear	0-78
7-18	4	710-1	2x4	Multiple Dip Tubes	Head	Good control - 2 sensors w/head	41-82
7-23	1	710-1	2x4	Plugged controls	Combined weir	Fine adj for optimum setting	29-68
7-23	2	710-1	2x4	Plugged controls	Higher heads	Higher max. diversion range	49-83
7-23	3	710-1	2x4	Plugged controls	Higher heads	Maximum range	47-83
7-24	1	710-1	1x4	Float Valve 2M	Head	Very short range - still linear	4-9
7-24	2	710-1	1x4	Float Valve 2M	Head 12.0"	Won't attach on interceptor side	39-84
7-24	3	710-1	1x4	Float Valve 2M	Head 8.0"	Lower range - attachment problem	21-49
7-24	4	710-1	1x4	Float Valve 2M	Head 10.0"	Same switching problem	30-75
7-25	1	710-1	1x4	Float Valve 2M	Diversion	Best control range	36-84
7-25	2	710-1	1x4	Half area 2M	Sensor	No improvement	36-81
8-15	1	813-1	4x4	Float Valve 4	Weir settings	Not as good range as 2"x4"	8-64
8-15	2	813-1	4x4	Float Valve 4	High combined weir	No control switching	50-50

Log of Sewer Regulator Element Tests (Continued)

Test Date	Test No.	Config. No.	Nozzle Size	Sensor	Parameter Tested	Results of Tests	Diversion Range
8-15	3	813-1	4x4	Float Valve 4	Lower head 9.0"	Narrow control range	40-50
8-15	4	813-1	4x4	Float Valve 4	Low combined weir	Increased control range	10-50
8-15	5	813-1	4x4	Float Valve 4	Head 17.0	Increase range	18-71
8-15	6	813-1	4x4	Float Valve 4	High combined weir	Increase range	8-69
8-19	2	818-1	4x4	Float Valve 4-5	Sensors	Improved linearity with area	11-62
8-20	1	818-1	4x4	Float Valve 6	Sensors	Greater area - improved linearity	12-60
8-20	2	818-1	4x4	Float Valve 6	Head 9.0"	Slightly improved range	12-64
8-20	3	818-1	4x4	Float Valve 6	Head 17.0	Slightly improved range	12-71
8-21	1	818-1	4x4	Float Valve 6	Flow over discharge	Greatly effects performance	4-30
8-29	1	829-1	2x4	Float Valve 2M	Diversion	Performance matches early 2x4	0-80
9-3	1	829-1	2x4	Bottles	Sensor	Narrow control range - not linear	0-63
9-4	1	829-1	2x4	Float Valve 2M	Weir settings	Affect performance significantly	2-75
9-4	2	829-1	2x4	Float Valve 2M	Higher head 16.0	Slightly improved control ranges	2-82
9-4	3	829-1	2x4	Float Valve 2M	Lower head 8.0	Lower control ranges	0-52
9-4	4	829-1	2x4	Float Valve 2M	Shrouded discharge	Large shroud need to separate flows	43-66

APPENDIX B

Orifice Equation

$$Q = C_D A \overline{2g\Delta h}$$

Q = Flow through orifice in cubic feet per second (CFS)

C_D = Orifice discharge coefficient (non-dimensional)

A = Area of orifice in square feet

g = Gravity constant 32.2 ft/sec/sec

Δh = Differential head in feet across orifice, i.e., upstream head minus downstream

In order to accurately use the orifice equation to calculate the flow through an orifice the head and orifice coefficient must be known. Test data taken from a fluidic irrigation water diverter by the Engineering Research Service, at Fort Collins, Colorado, provide flow vs supply head data for a known nozzle size diverter, see Figure B-1.

These data were used with the orifice equation to obtain the values of discharge coefficient vs differential head, see Figure B-2.

The experimental curve of discharge coefficient vs supply head was then used with the orifice equation to form the nomograph of Figure 10 covering a nozzle area range from 0.1 to 10 square feet, a head range from 1.0 to 100 feet and orifice coefficients from 0.8 to 1.2.

The nomograph obtained from the orifice equation and irrigation diverter (8" x 8") test data were then compared to the data from the 1/2" x 1/2" irrigation diverter used in the predictive analysis and the 2" x 4" fluidic sewer diverter, see Figures B-3 and B-4 with the following results.

Comparison of Test Data

1/2" x 1/2" Nozzle Irrigation Diverter, Figure B-3

$A = 1.73\ (10^{-3})$ sq ft $\Delta h = .455$ ft $C_D = 1.2$ $h_i/h_n = 12$

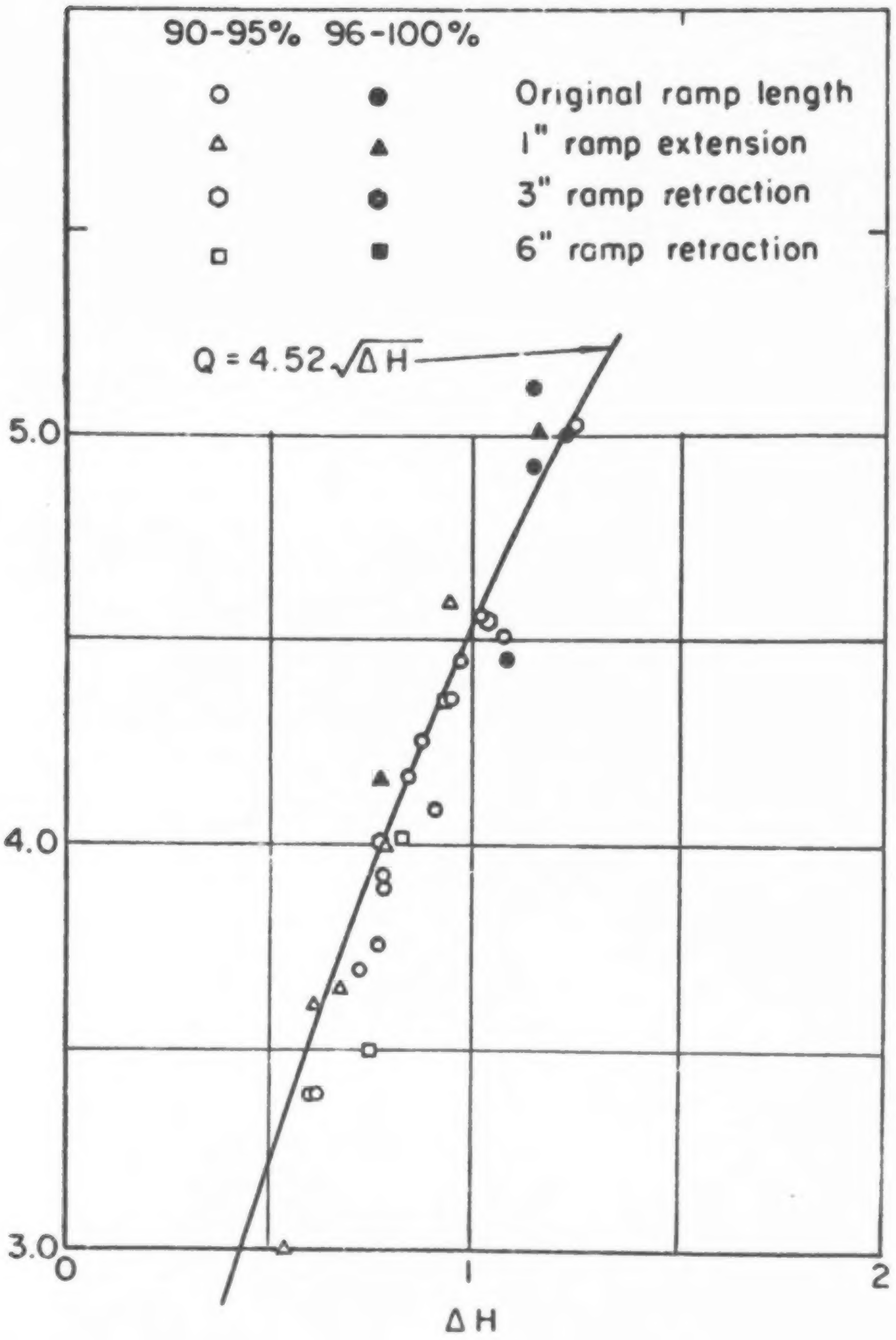

Figure B-1. Relationship of Discharge to the Differential Head Across the Diverter. Fluidic Irrigation Diverter 8" x 8" Nozzle

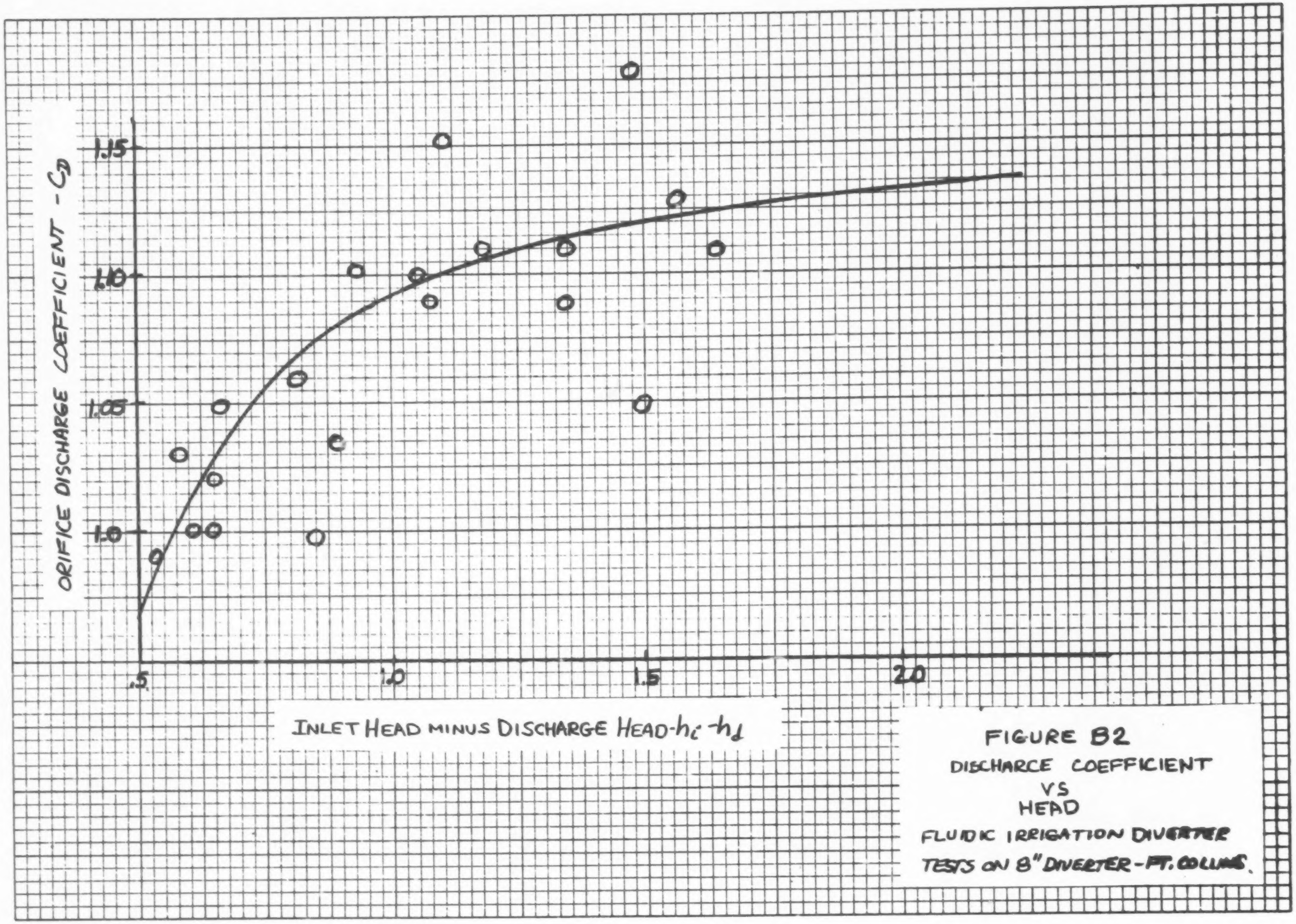

FIGURE B2
DISCHARCE COEFFICIENT
VS
HEAD
FLUIDIC IRRIGATION DIVERTER
TESTS ON 8" DIVERTER - FT. COLLINS.

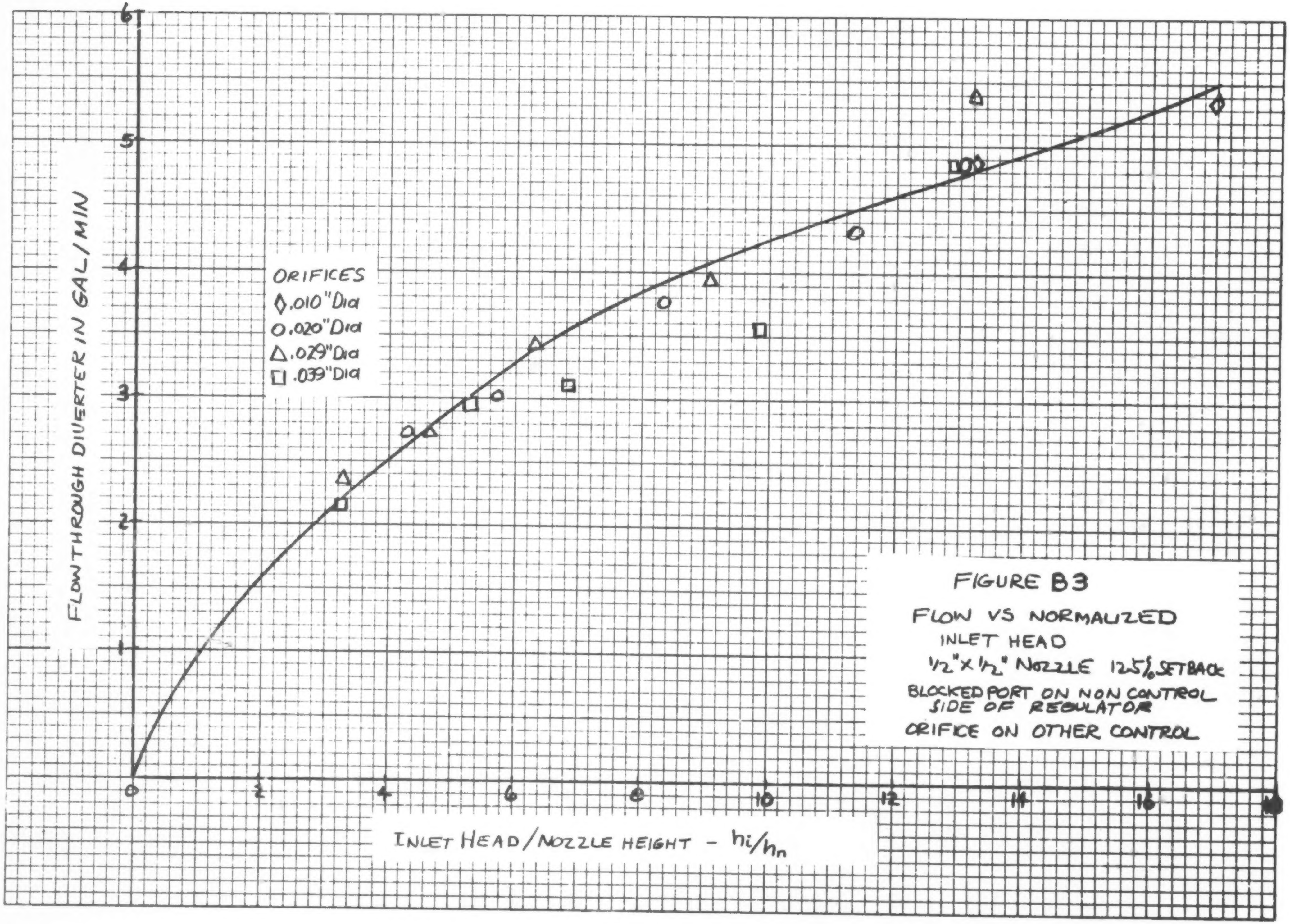

FIGURE B3

FLOW VS NORMALIZED INLET HEAD

1/2" X 1/2" NOZZLE 12.5% SETBACK

BLOCKED PORT ON NON CONTROL SIDE OF REGULATOR

ORIFICE ON OTHER CONTROL

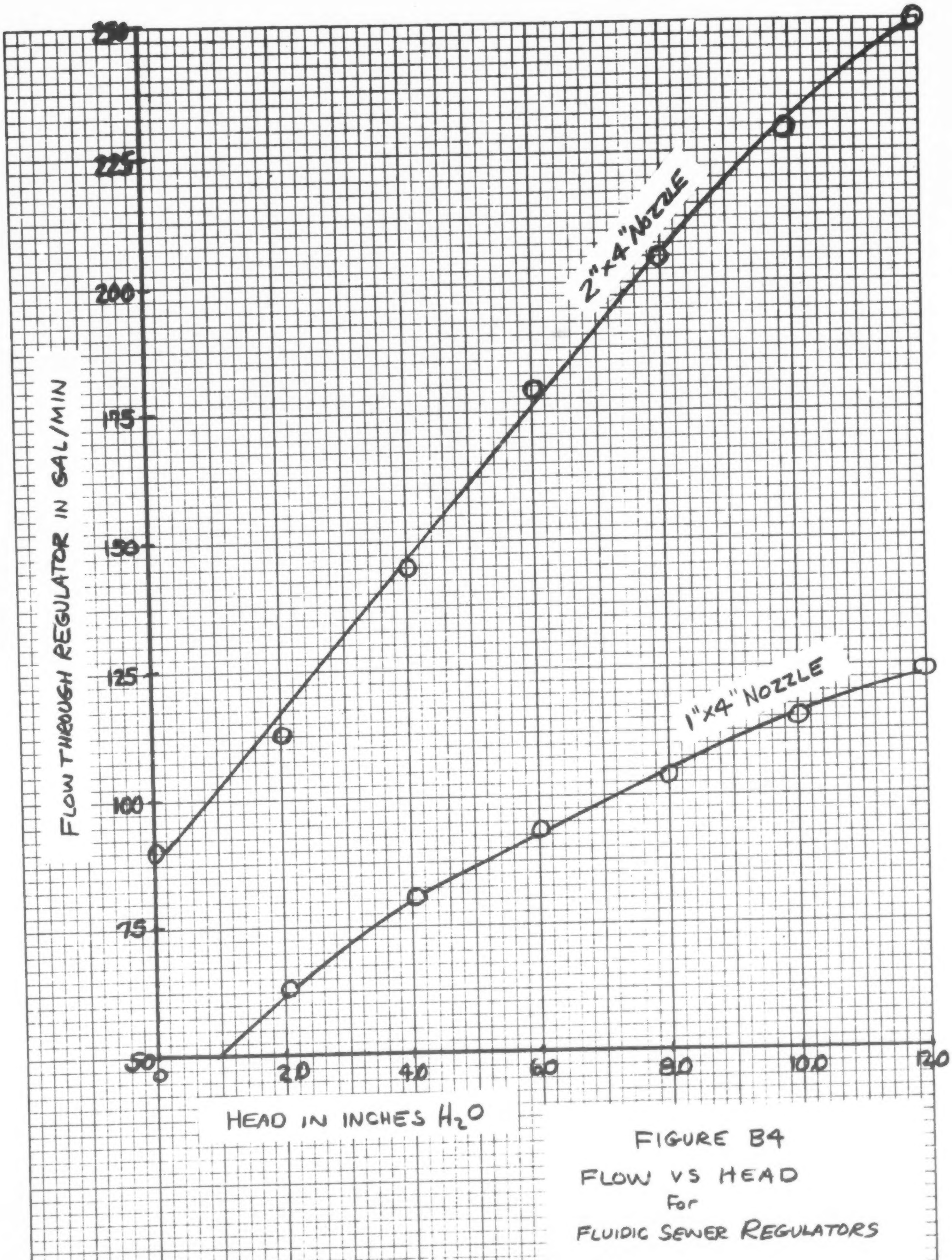

FIGURE B4
FLOW VS HEAD
For
FLUIDIC SEWER REGULATORS

Flow from Figure B-3 measured

$Q = 5$ gpm $= 1.11\ (10^{-2})$ cfs

Flow from nomograph Figure 10

$Q = 1.1\ (10^{-2})$ cfs

Agreement of flows was as good as the reading accuracy of the nomograph or approximately 1%.

2' x 4" Nozzle Sewer Regulator, Figure B-4

$A = 5.5\ (10^{-2})$ sq ft $\Delta h = .915$ ft $C_D = 1.2$

Flow from Figure B-4 measured

$Q = 228$ gpm $= .507$ cfs

Flow from nomograph Figure 10

$Q = .51$ cfs

Agreement better than 1% indicating the nomograph of Figure 10 is a reliable source of design data for fluidic sewer regulators.

APPENDIX C

Performance Design Data

Diversion vs control orifice areas for various bias orifice areas were taken from the 1/2" x 1/2" nozzle irrigation diverter at various supply heads, see Figures C-1 and C-2.

Diversion vs supply head data were taken for sewer regulator geometries having nozzle and aspect ratios as follows:

Aspect Ratio	Nozzle Size
2	2" x 1"
1	4" x 4"
.5	2" x 4"
.25	1" x 4"

Actual data from test of these model regulators are shown in Figure C-3. Inconsistencies in the data curves resulted from minor variations in the geometries of the regulators tested. The misplacement of the data points from the 4" x 4" nozzle regulator were caused by a long nozzle which reduced the venturi effect, see Figure 50.

Diversion vs height of the combined discharge weir were measured over a complete range of weir settings and supply heads as shown in Figure C-4. The test data show that raising the combined weir increases its resistance and diverts more flow to the interceptor. As the combined weir is lowered diversion increases until the weir gets so low that an air pocket forms along the top of the element and destroys the wall attachment effect by equalizing control pressures and permitting direct communication from ambient air to the interceptor control port. The water flow is supercritical in this case. The combined weir tests were taken for an interceptor weir exit area of 12.2 in^2 which was within the operating zone of the regulator. Figures C-5, C-6, C-7, and C-8 show data taken for maximum and minimum diversion as a function of the interceptor weir area which produces a loading effect somewhat like that of the combined weir. If the interceptor area is too great the coanda effect won't form as a result of supercritical flow conditions. Too small an area affects maximum dry weather flow diversion to the interceptor, so that some flow goes over the combined weir. Data were taken for two nozzle sizes and three supply heads, see graphs.

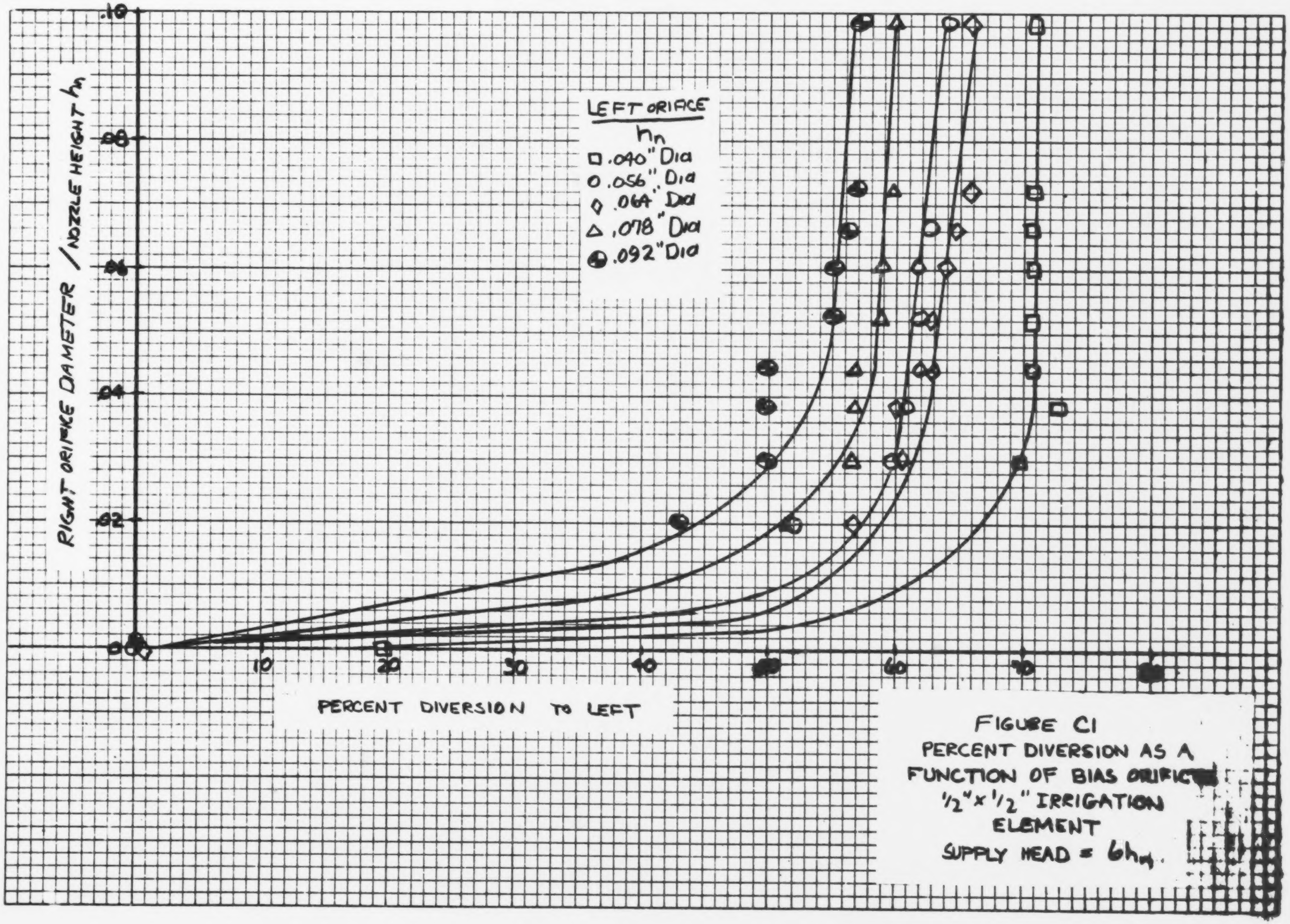

FIGURE C1
PERCENT DIVERSION AS A FUNCTION OF BIAS ORIFICE
1/2" x 1/2" IRRIGATION ELEMENT
SUPPLY HEAD = $6h_n$

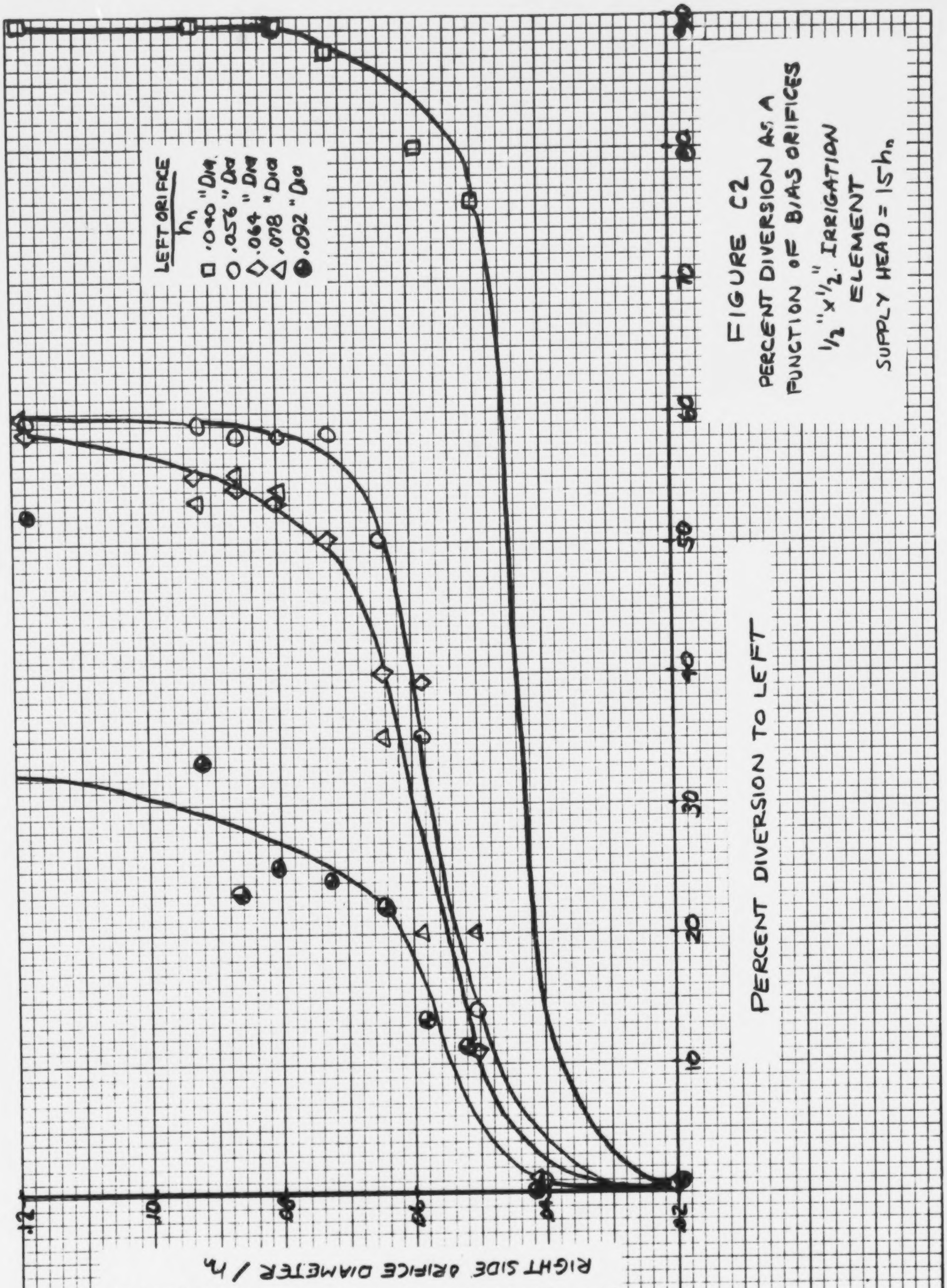

FIGURE C2
PERCENT DIVERSION AS A
FUNCTION OF BIAS ORIFICES
$1/2$"x$1/2$" IRRIGATION
ELEMENT
SUPPLY HEAD = $15 h_n$

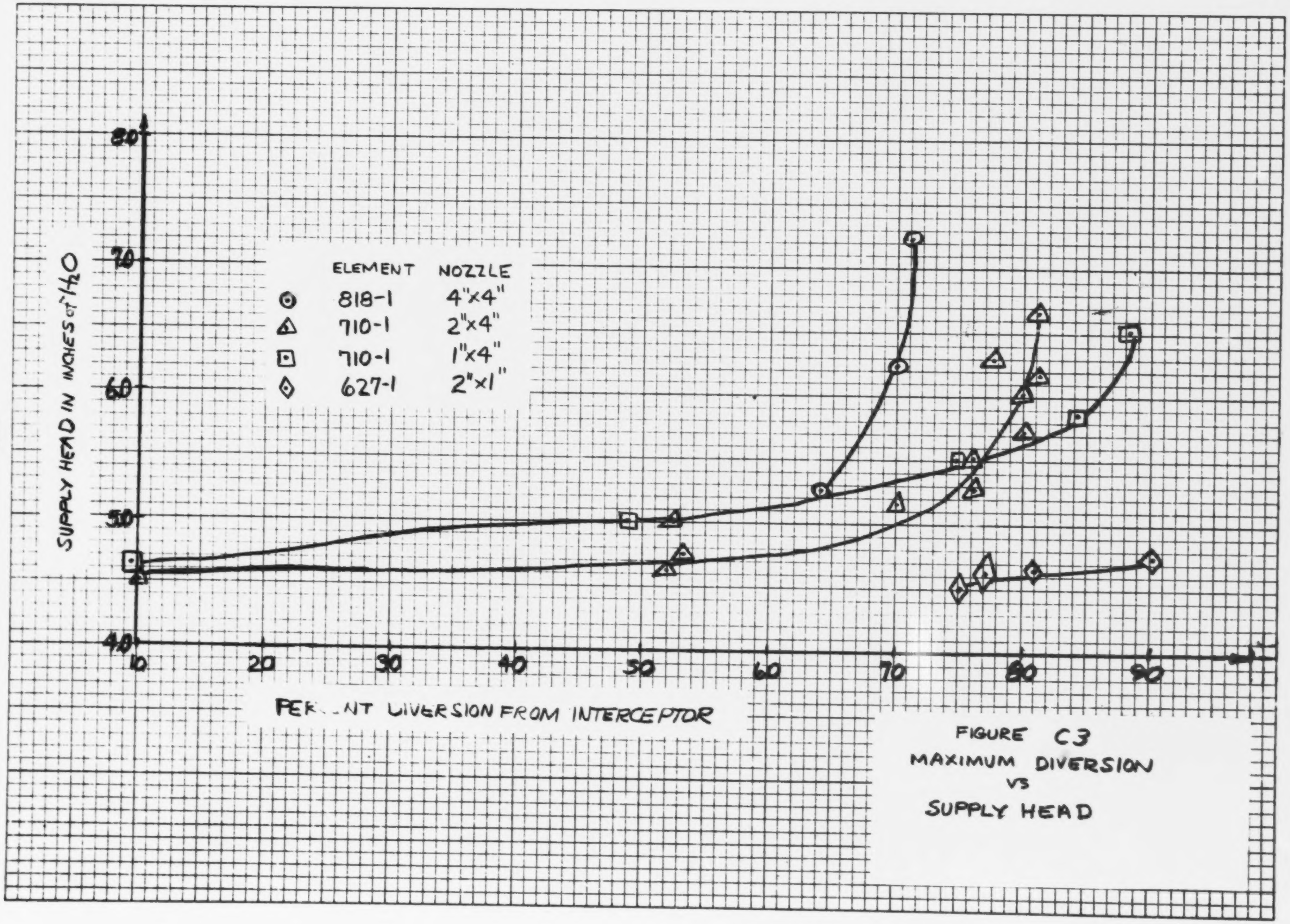

FIGURE C3
MAXIMUM DIVERSION
VS
SUPPLY HEAD

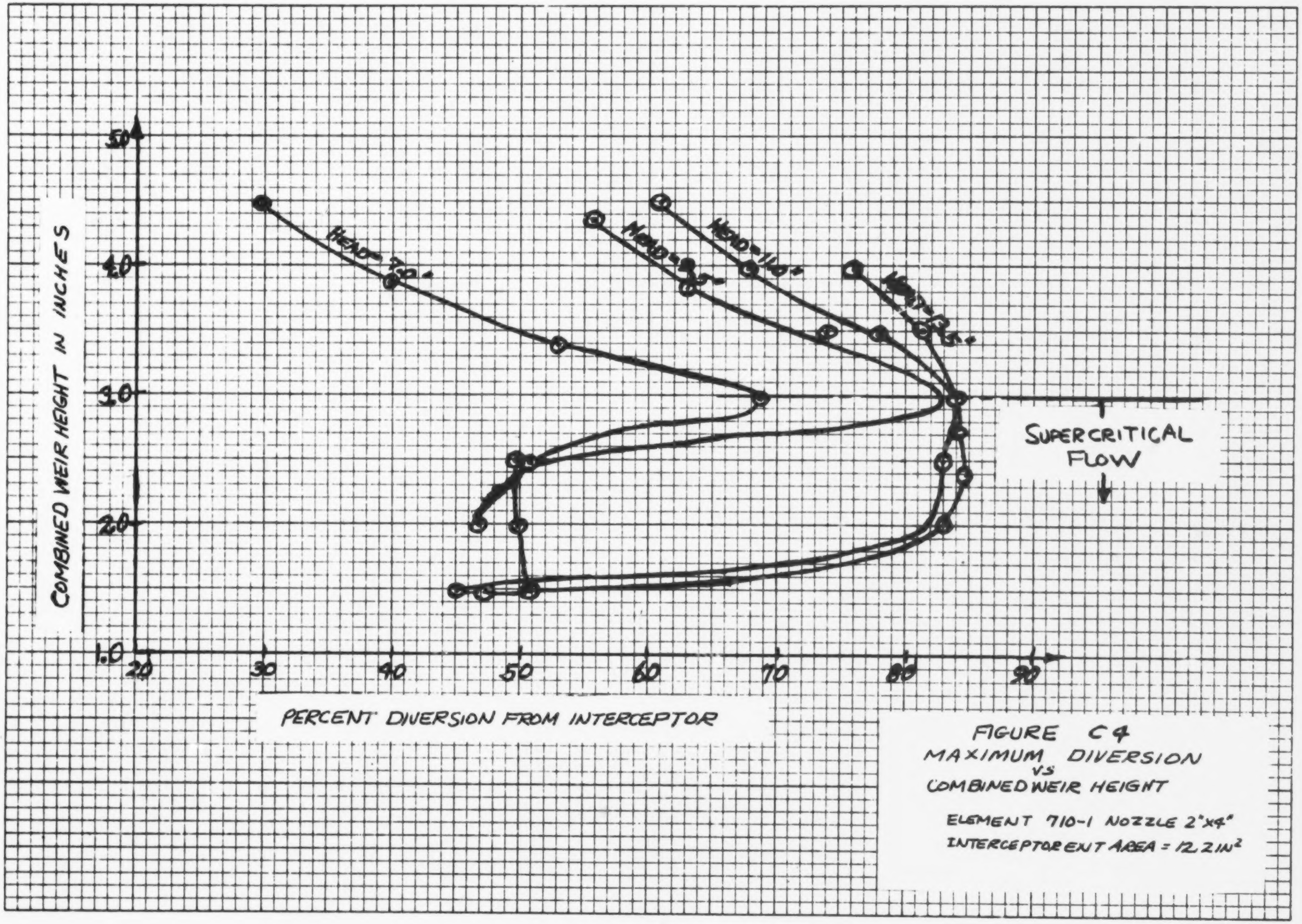

FIGURE C4
MAXIMUM DIVERSION vs COMBINED WEIR HEIGHT
ELEMENT 710-1 NOZZLE 2"x4"
INTERCEPTOR ENT AREA = 12.2 IN²

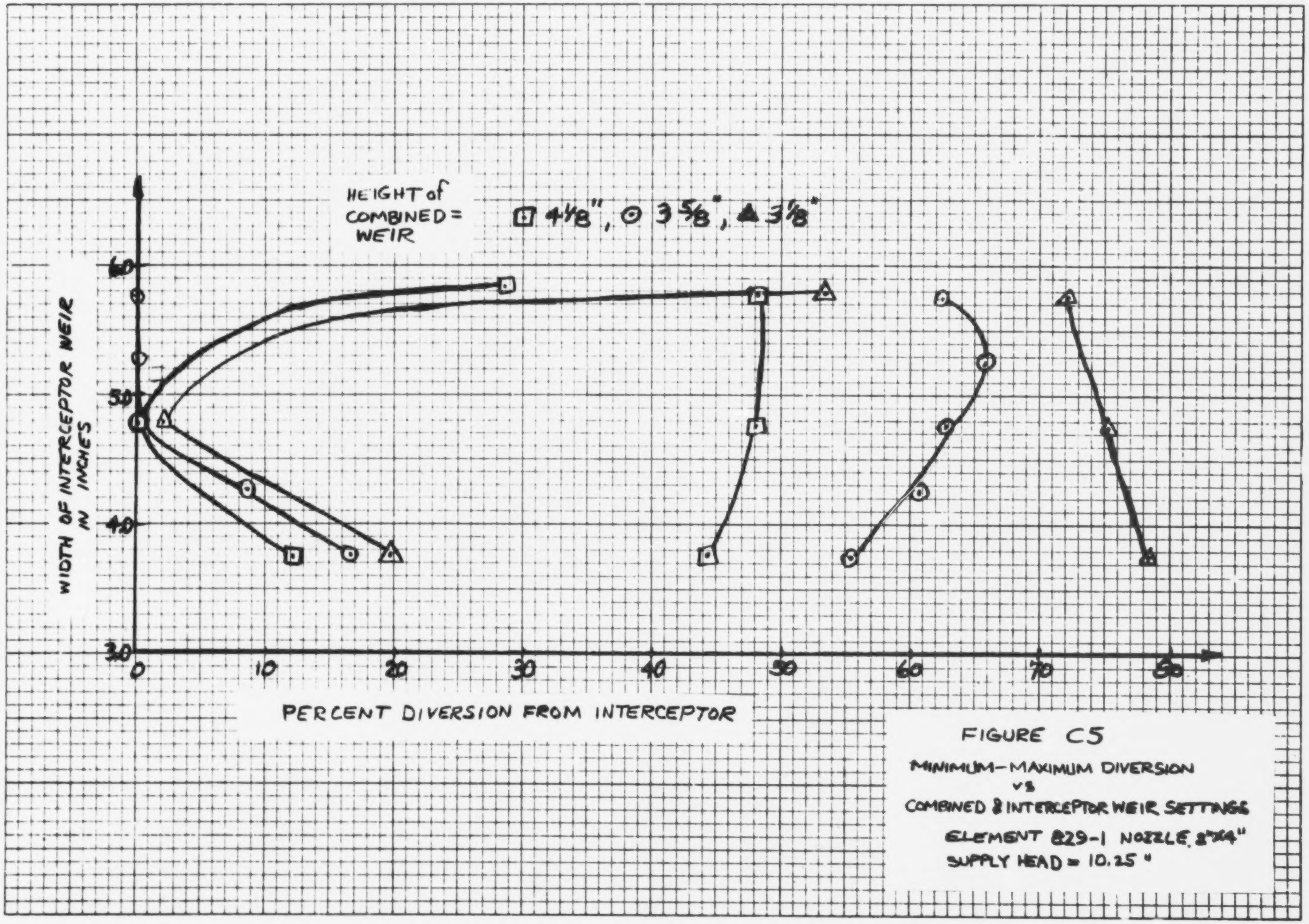

FIGURE C5

MINIMUM–MAXIMUM DIVERSION
VS
COMBINED & INTERCEPTOR WEIR SETTINGS
ELEMENT 829-1 NOZZLE 2"X4"
SUPPLY HEAD = 10.25"

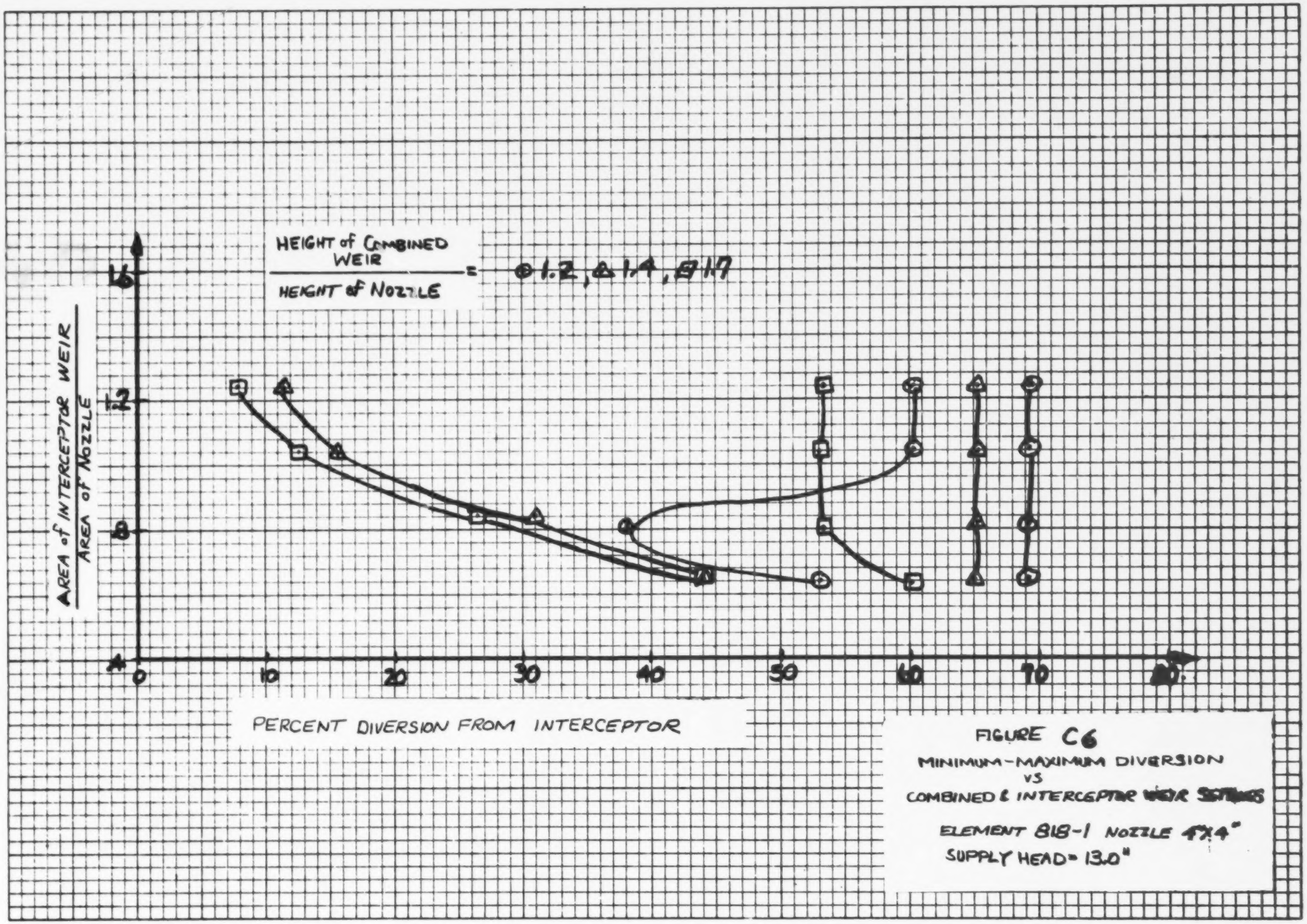

FIGURE C6
MINIMUM-MAXIMUM DIVERSION
VS
COMBINED & INTERCEPTOR WEIR SETTINGS
ELEMENT 818-1 NOZZLE 4"X4"
SUPPLY HEAD = 13.0"

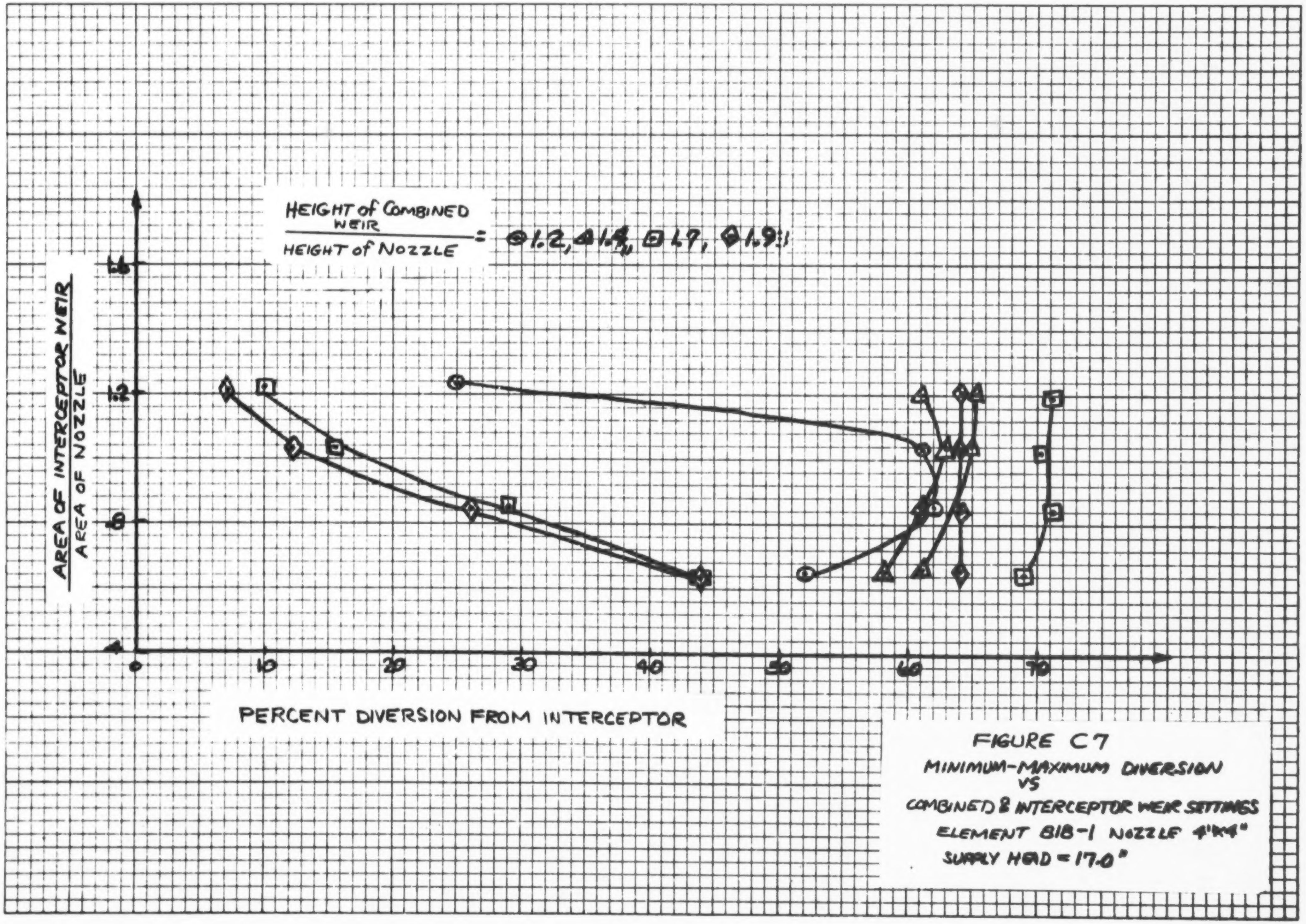

FIGURE C7

MINIMUM-MAXIMUM DIVERSION
VS
COMBINED & INTERCEPTOR WEIR SETTINGS
ELEMENT 818-1 NOZZLE 4"x4"
SUPPLY HEAD = 17.0"

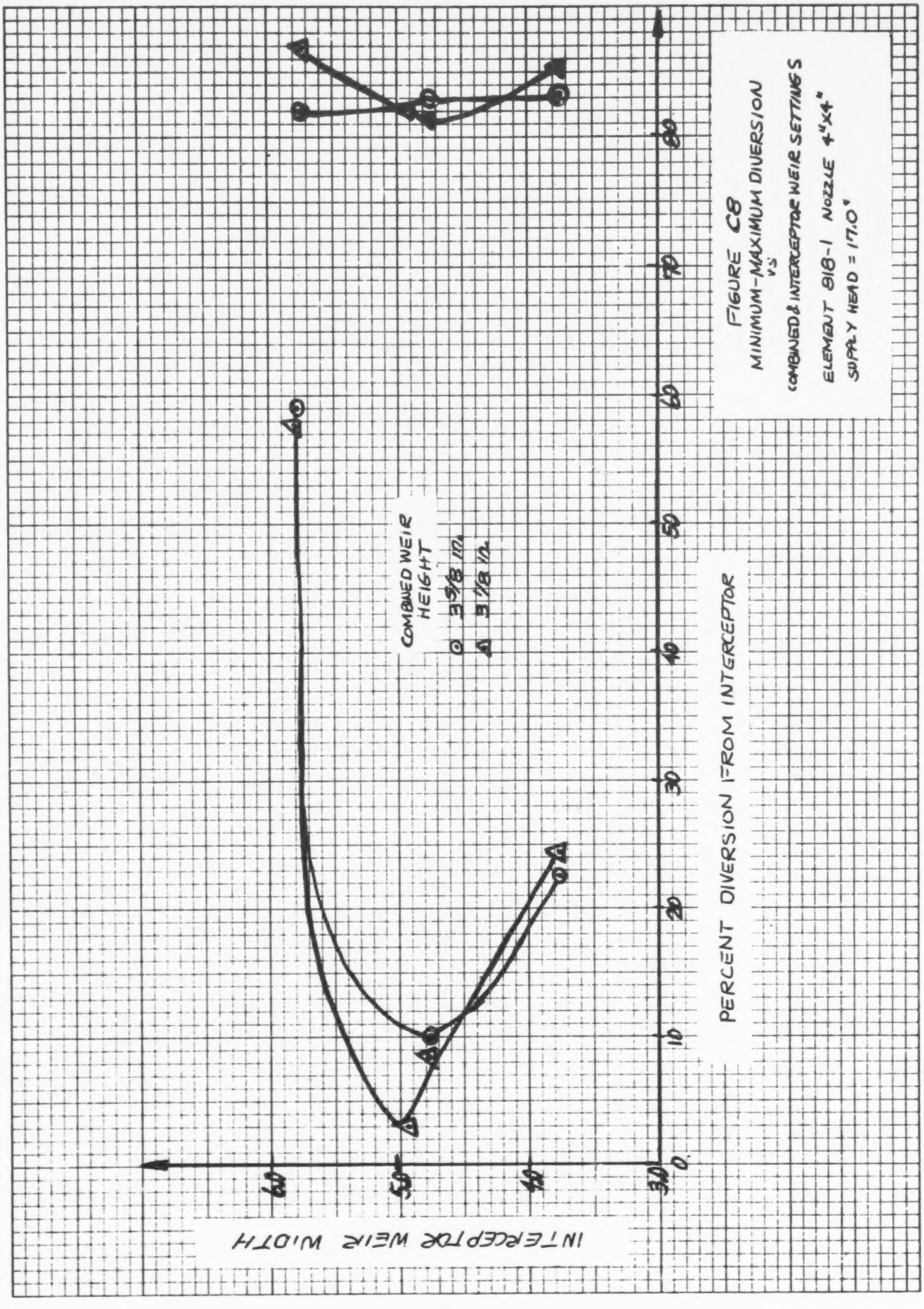

FIGURE C8
MINIMUM-MAXIMUM DIVERSION
VS
COMBINED & INTERCEPTOR WEIR SETTINGS
ELEMENT 818-1 NOZZLE 4"X4"
SUPPLY HEAD = 17.0'

Percent diversion vs the height of water in the interceptor data were taken for the best analog geometry with the most linear sensor to determine diversion range and linearity over a wide range of heads, see Figure C-9. Results showed that linearity was good over the operational head range; however, diversion performance dropped sharply for supply heads below $3.5\,h_n$ (h_n = nozzle height). Diversion performance showed improvement with head until a head of $5\,h_n$ was reached at which point best performance is reached. Figures C-11 and C-12 show the combined interceptor sewer test setup with the float valve, used to obtain the diversion data discussed above.

In order to represent the change in interceptor level as a more meaningful parameter, the sensor float valve calibration was expressed as area change of sensor over area of regulator nozzle as follows: (see Figures C-10 and C-13)

$$\text{Sensor Area Change Ratio} = \frac{\Delta A_1 + \Delta A_2}{A_N} \quad (10^{-3})$$

ΔA_1 = Change in combined control area

ΔA_2 = Change in interceptor control area

A_N = Area of nozzle

Reference Point

Flow diverted 100% to interceptor

$\Delta A_1 = 0 \quad \Delta A_2 = 0$

As the interceptor water level increases area ΔA_2 (interceptor control area) is opened until the 50-50 diversion point is reached. As the interceptor level continues to change ΔA_1 (combined control area) is closed until at 100% diversion from the interceptor, ΔA_1 is fully closed and ΔA_2 is fully opened giving a sensor area change ratio of:

$$\frac{A_C + A_C}{A_N} = \frac{2A_C}{A_N}, \; A_C = \text{Area of control orifice}$$

Air flow through the control ports of a fluidic sewer regulator as a function of the percent diversion was plotted as an air/water ratio for a 2" x 4" and 4" x 4" sewer regulator being controlled by a mechanical float valve, see Figure C-14. Test observations and data confirmed the air flow

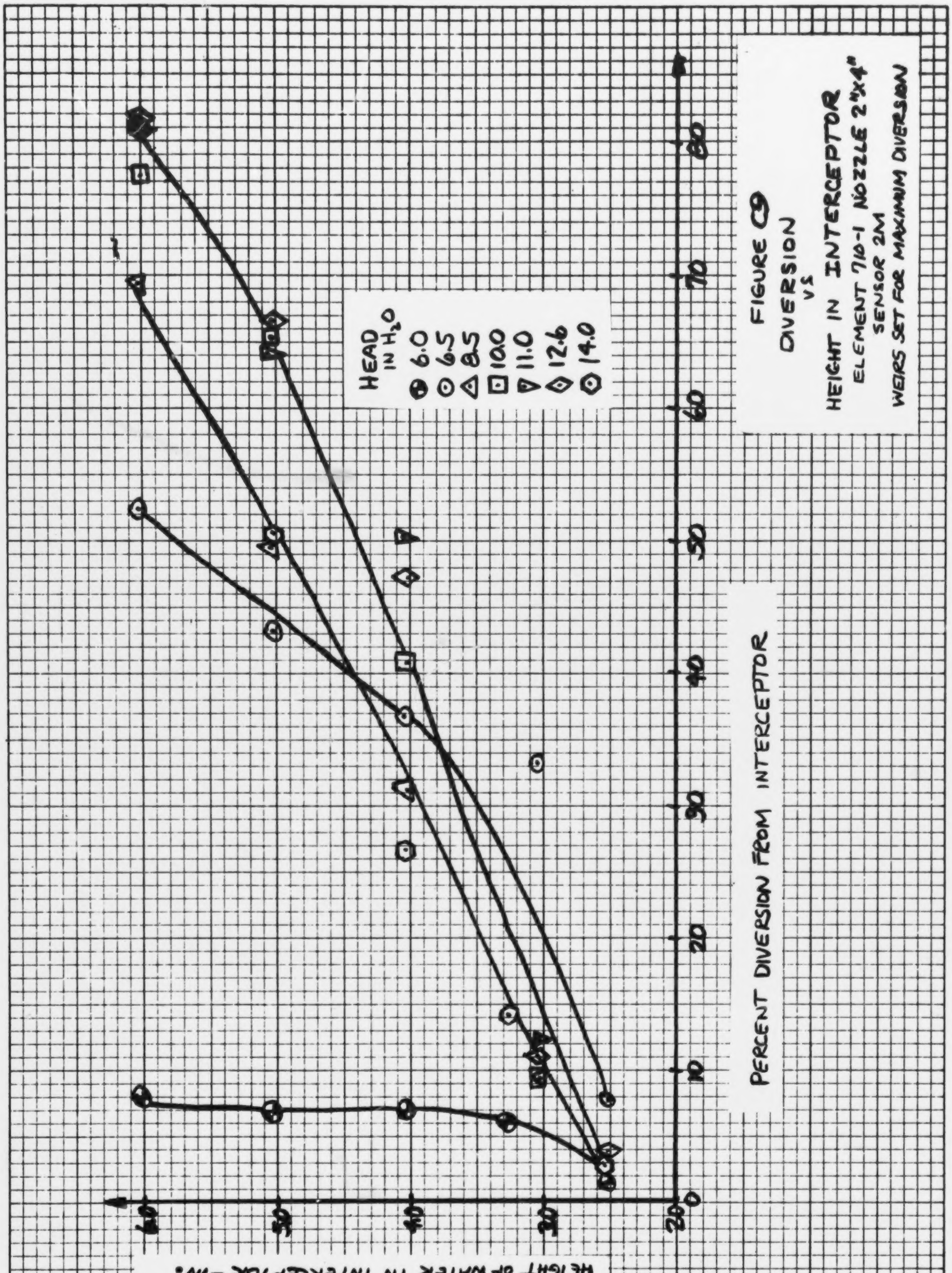

FIGURE C9
DIVERSION
VS
HEIGHT IN INTERCEPTOR
ELEMENT 710-1 NOZZLE 2"x4"
SENSOR 2M
WEIRS SET FOR MAXIMUM DIVERSION

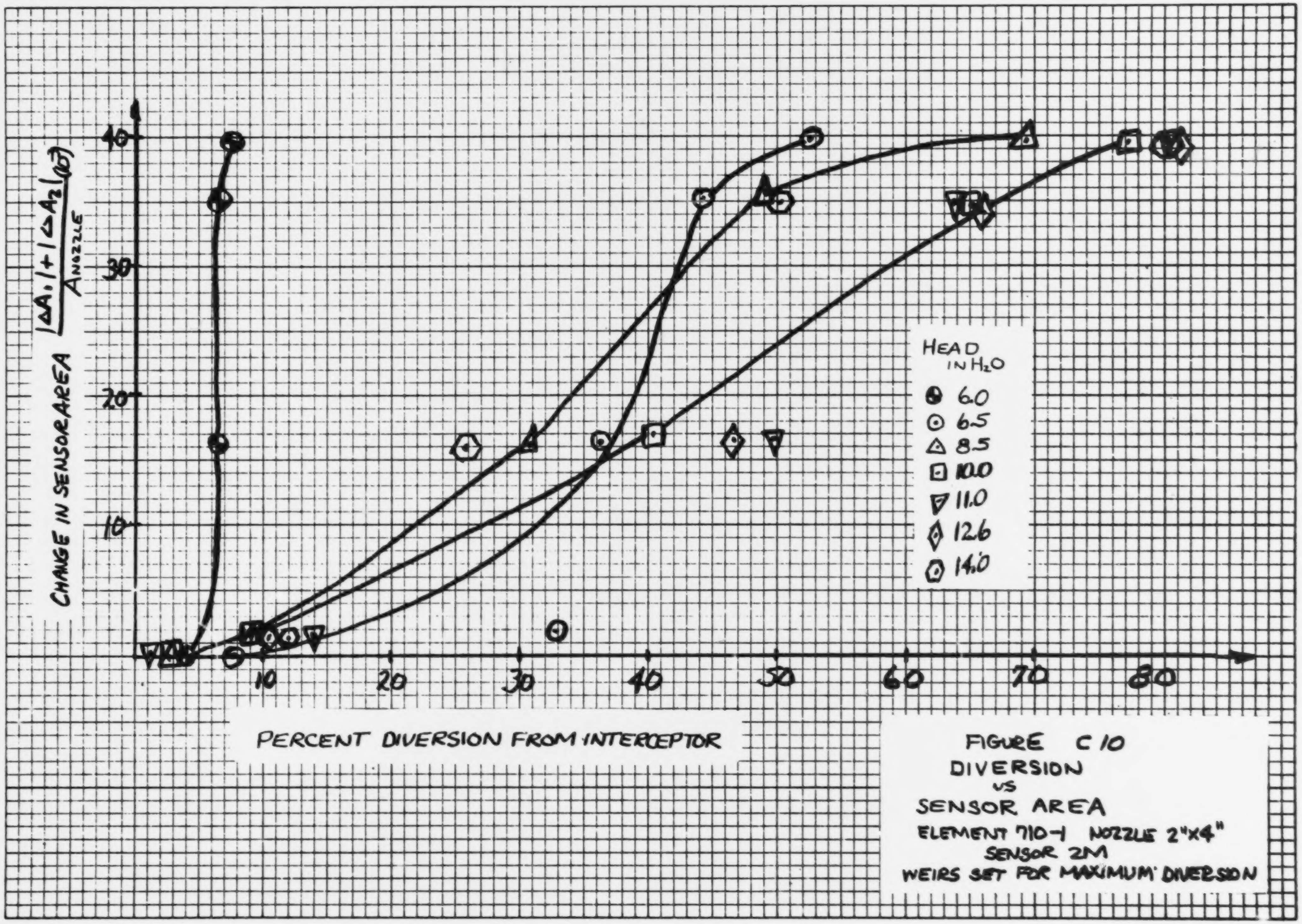

FIGURE C 10
DIVERSION
VS
SENSOR AREA
ELEMENT 710-1 NOZZLE 2"x4"
SENSOR 2M
WEIRS SET FOR MAXIMUM DIVERSION

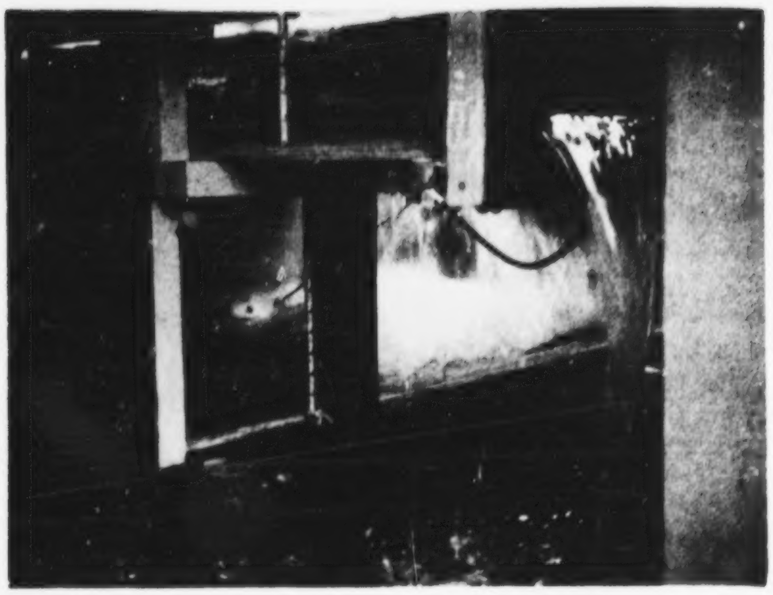

Figure C-11. Low Diversion, Low Interceptor Water Level
Float Valve Control

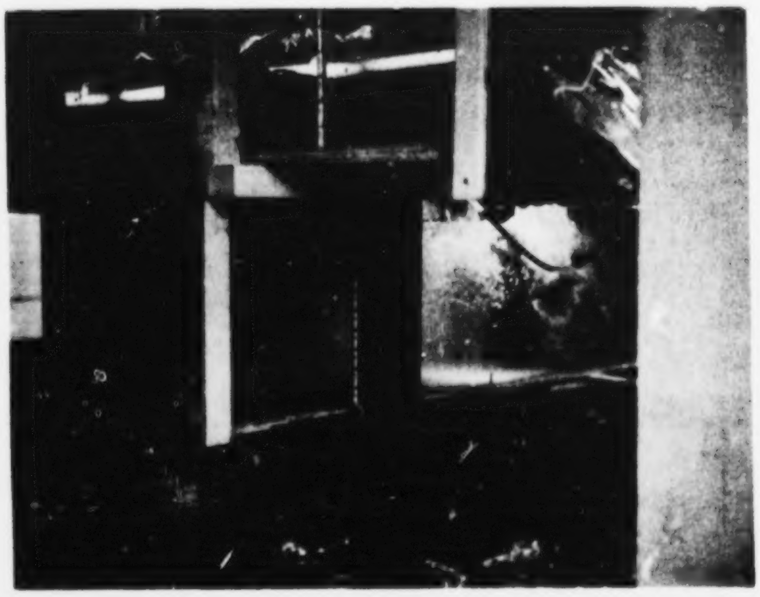

Figure C-12. High Diversion, Loaded Interceptor
Float Valve Control

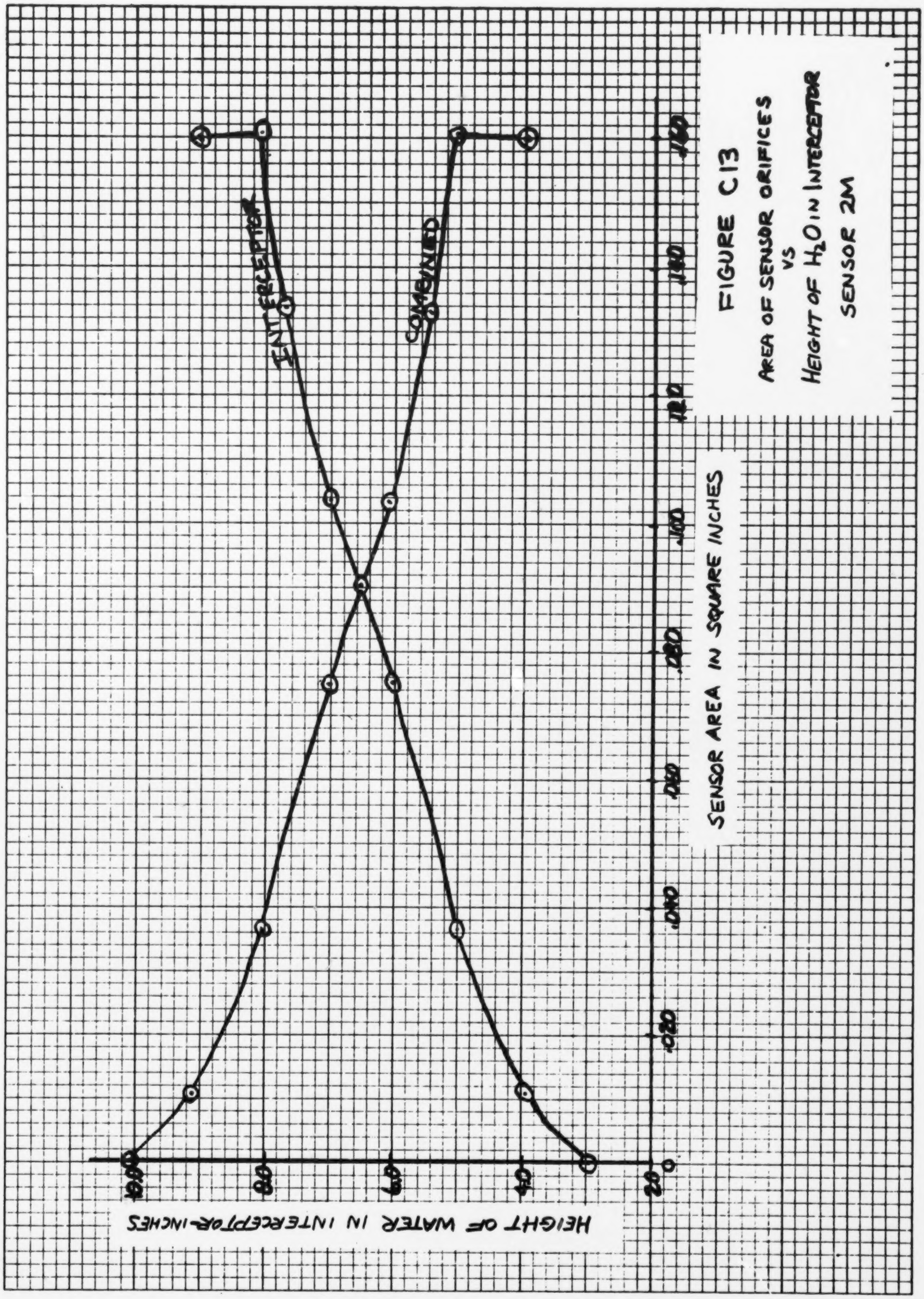

FIGURE C13
AREA OF SENSOR ORIFICES
VS
HEIGHT OF H_2O IN INTERCEPTOR
SENSOR 2M

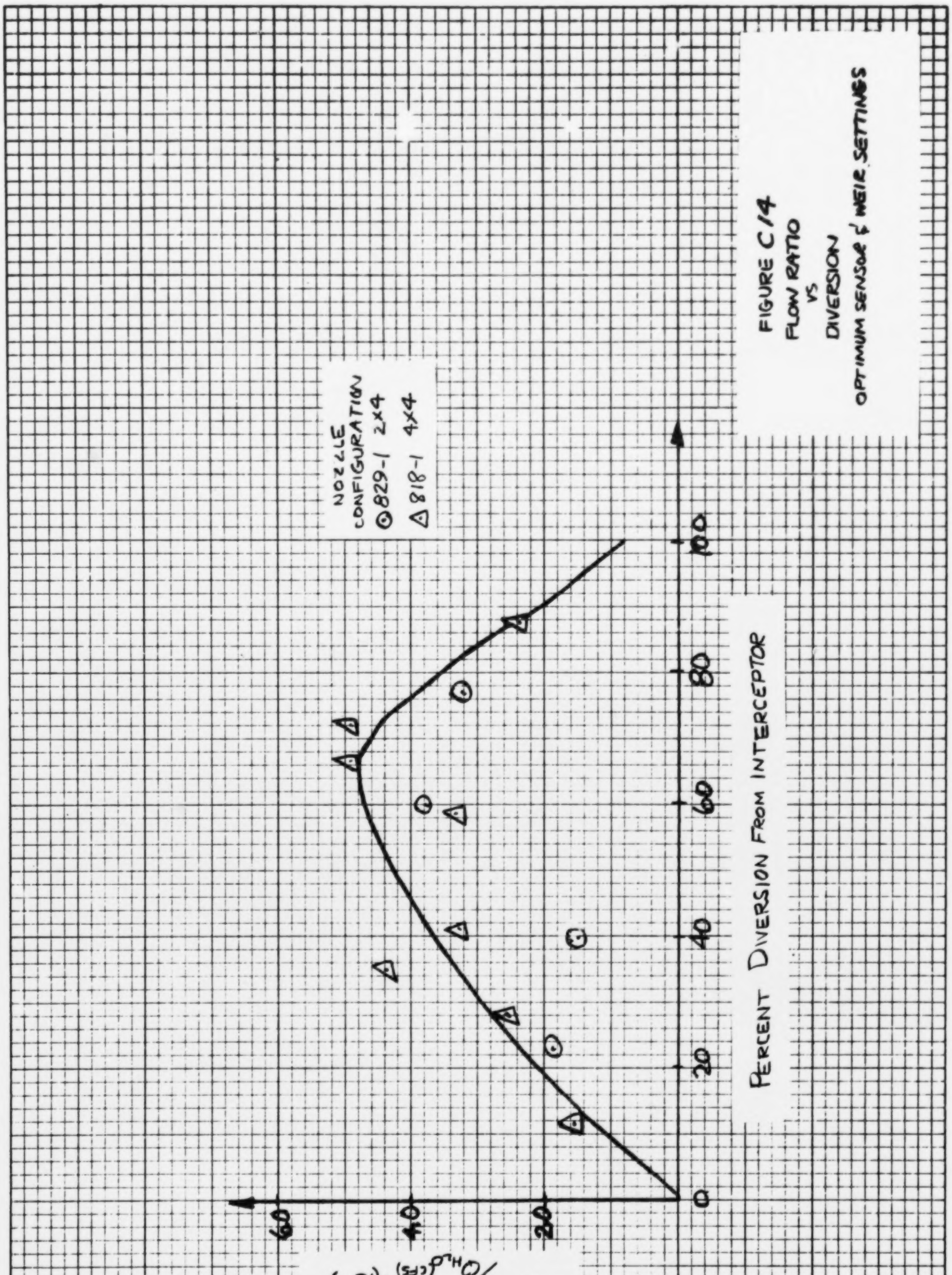

FIGURE C14
FLOW RATIO
VS
DIVERSION
OPTIMUM SENSOR & WEIR SETTINGS

characteristic as shown. As the control port is opened from a maximum diversion setting aspiration begins and increases until the 50-50 diversion point is reached when the port is fully open. Sensor tests showed that further increase in sensor area has no effect; that is, the regulator is getting all the air it needs. As the diversion increases above the 50 percent level, the aspiration in the open control line actually drops as a result of the decreased venturi effect when the jet stream is directed away from the control pocket.

APPENDIX D

Fouling Analysis

The table shown on the following page is the test data taken as part of the fouling analysis. The test configuration used, see Figure 76, had a very pointed splitter which was much more susceptible to fouling than more rounded types which were found to have the same diversion performance. Half of the fouling hang up caused by the twigs were caused by the forks snagging the pointed splitter. The remainder of the hang ups caused by twigs resulted in the long (10") twig lodging crosswise at the nozzle. It is quite possible that under actual conditions where a reasonably long approach line supplies the regulator, long objects such as twigs and rolls of paper will align themselves in the water stream with their longest dimension in the direction of the stream, allowing them to pass through the regulator rather than hang up crosswise.

Fouling Test Data

Regulator Element Nozzle Size 2" x 3-1/4"
Supply Head 9-1/4"
Interceptor Weir Open

Code Letter Fig. 4-16	Subject Length	Number of Forks	Total Passes	Passed Through	Hung Up Then Passed Through	Hung Up	Remarks
A	Twig-6.5"	2	10	5	3	2	Fork caught splitter
B	Twig-3.0"	0	10	10	0	0	
C	Twig-6.0"	2	10	8	1	1	Large fork caught pointed splitter
D	Twig-6.5"	0	10	9	1	0	
E	Twig-4.5"	2	10	9	1	0	
F	Twig-3.5"	1	10	10	0	0	
G	Twig-4.0"	1	10	10	0	0	
H	Twig-10.0"	1	10	5	2	3	Caught in neck of nozzle
-	Paper-2"x3"	-	10	10	0	0	
-	Paper-4"x5"	-	10	10	0	0	
-	Paper-2"x6"	-	10	10	0	0	
-	Paper-10"x16"	-	10	8	0	2	Hung up on splitter

TOTAL HANG UPS 8

APPENDIX E

Control Line Sizes

The control line I.D. vs length vs regulator nozzle area data as shown in Figure 13 was derived with the following considerations.

The maximum airflow through the control port occurs at the 50-50 diversion point, see Figure 70.

The maximum airflow for fluidic sewer regulators is 5×10^{-2} times the water flow through the regulator, see Figure 70.

The optimum sensor area for linear analog control of a sewer regulator is $20\ (10^{-3})\ A_N$ (A_N = area of nozzle -in^2), see Figures 62 and 63.

Knowing the maximum area and maximum airflow we can calculate the pressure drop across the sensor orifice with zero control line length, using Figure E-1.

Using the sensor area vs diversion characteristic for linear analog control shown in Figures 62 and 63, it was assumed that a degradation in diversion performance of 10% would be tolerated as a result of the control line length to be added to the sensor control orifice.

The area change corresponding to a 10% degradation in diversion performance, from Figures 62 and 63, is $5\ (10^{-3})\ A_N$ (A_N = area of nozzle).

It was then assumed that the same maximum control airflow would pass through an orifice with new area equal to the optimum sensor area minus the area change corresponding to the 10% degradation in diversion performance:

$$\begin{aligned}\text{New area} &= \left[20\ (10^{-3}) - 5\ (10^{-3})\right] A_N \\ &= 15\ (10^{-3})\ A_N \quad (A_N = \text{area of nozzle})\end{aligned}$$

Using the maximum airflow and this new area the pressure drop across the new area is obtained from Figure E-1.

The difference in pressure drops (ΔP) between the pressure drop across the optimum sensor orifice area and the sensor orifice area which would provide a diversion change of 10 percent is then the tolerable pressure drop in the control lines when the control orifice is fully open and airflow is at its maximum value.

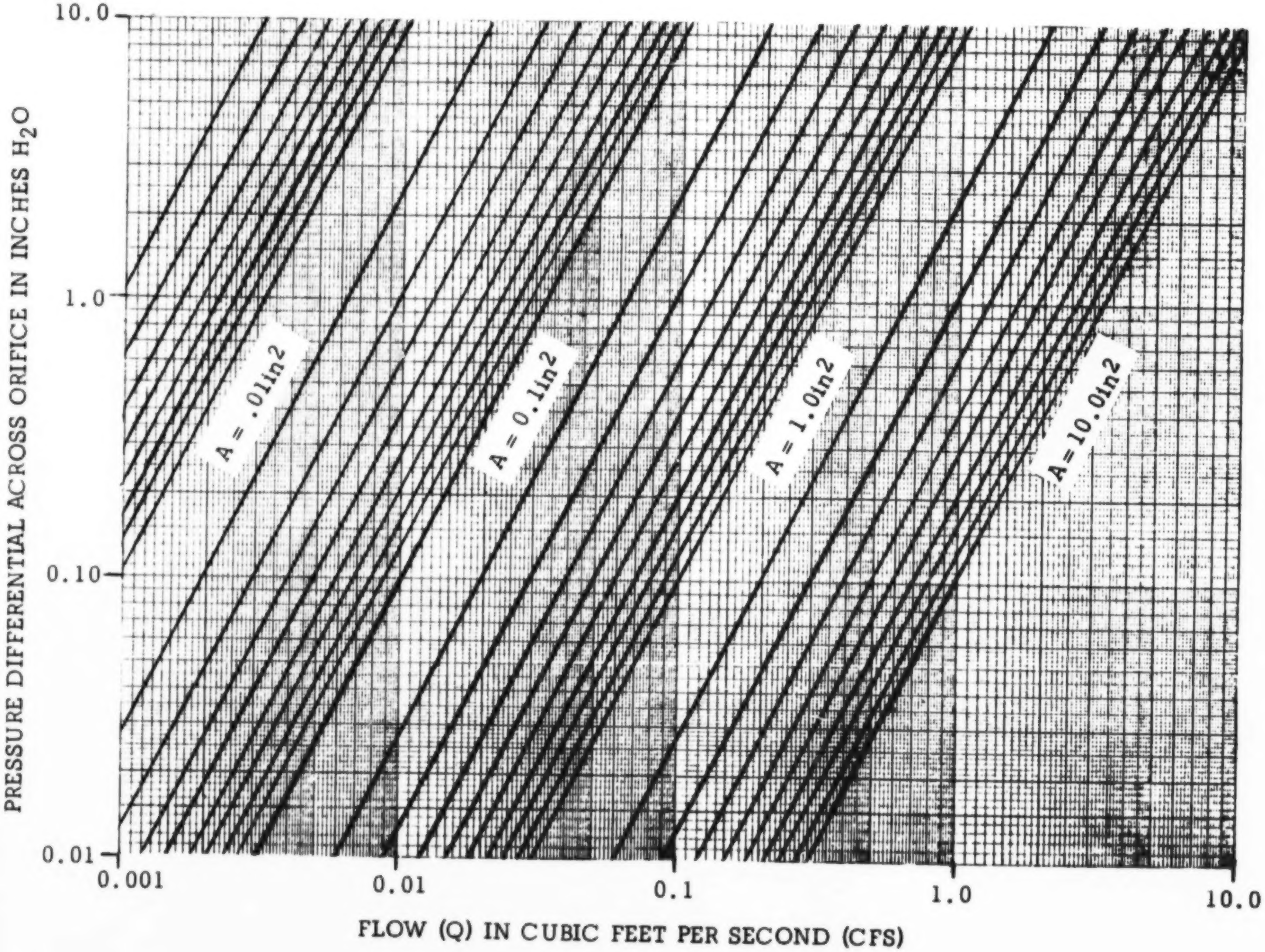

Figure E-1. Air Flow Through Orifice

The pressure drop (ΔP) was then used with the nomograph showing Figure E-2* to determine the minimum I.D. (internal diameter) of a 100 foot control line. By using various scale factors of ΔP with the nomograph of Figure E-2, a family of curves of control line I.D. vs length of control line vs regulator nozzle area was obtained. (See Figure 13.) The air pressure drop nomograph (see Figure E-2) used to obtain the control pipe size is demonstrated through the following example:

> The temperature of the fluid on the "t" scale is connected with the exhaust pressure of the pipe on the P scale intersecting index A at point a.
>
> $P = 0$ psig, $t = 70^\circ F$
>
> Point a is then connected to the flow rate through the pipe as shown on the "V" scale and intersecting index B at point b.
>
> $V = 1.0$ scfs $= 60.0$ scfm
>
> Point b is then used with the allowable pressure drop for 100 foot of control pipe from scale ΔP_{100} and the intersection of a line through these two parameters gives the minimum required control line size.
>
> $\Delta P = .04$ psig
>
> Minimum I.D. $= 2.9$ inches

---

*This figure is based on an article "Air Pressure Drop Nomograph," by F. Kaplan, Kaiser Engineers, appearing in the April, 1967, issue of Controls Engineering Magazine.

Figure E-2. Air Pressure Drop Nomograph

Pressure - PSIG
Pressure Line Drop/100 Feet = PSIG
Flow Through Line - SCFM
Temperature of Fluid - deg F
I.D. of Tubing - inches